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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

AUGUST 1953

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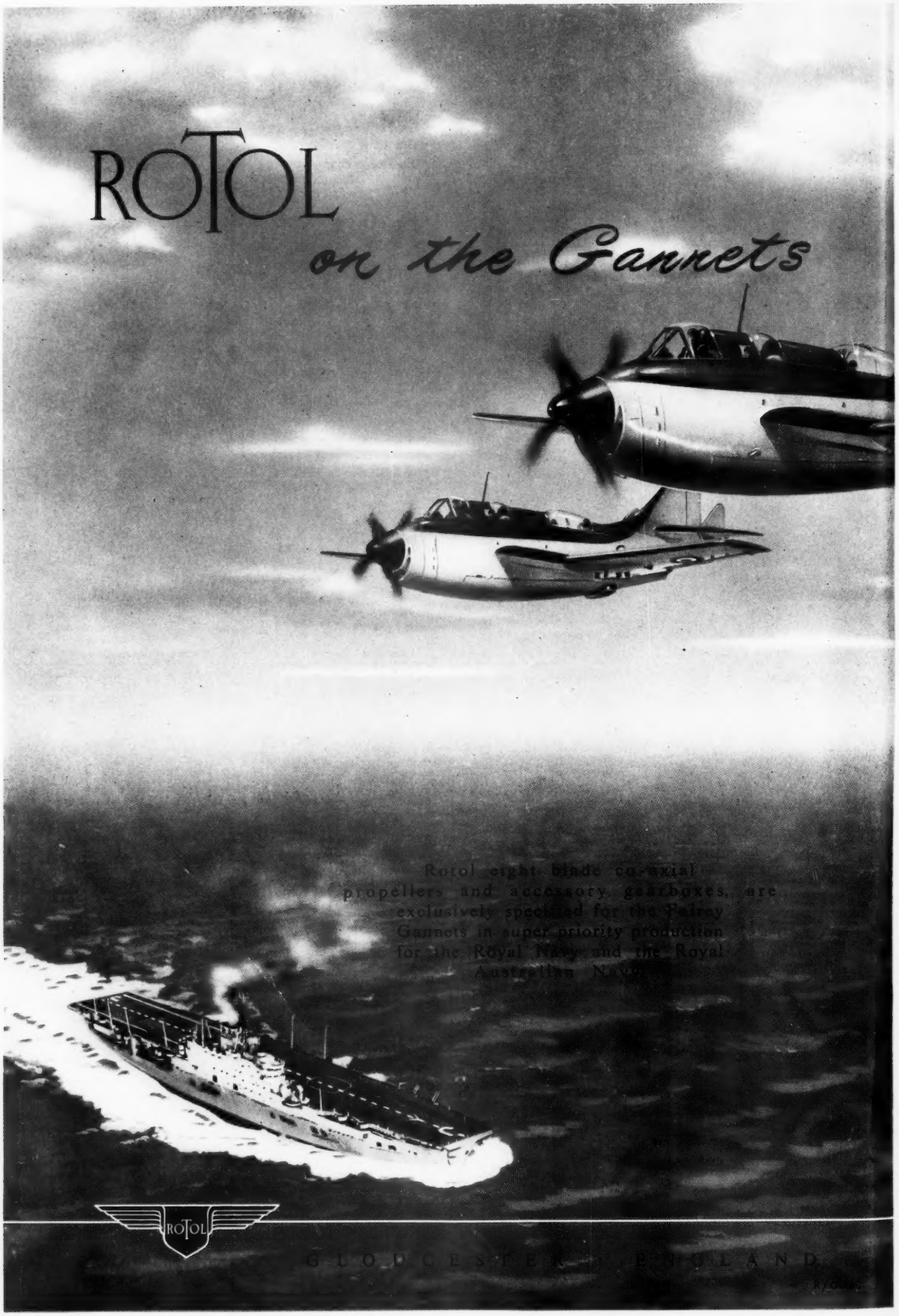
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Journal of

THE ROYAL AERONAUTICAL SOCIETY

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None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless stated otherwise.

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Secretary's News Letter

August 1953

ELSEWHERE in this JOURNAL a description of the Garden Party is given, and thanks are paid to all those who helped to make a success of the Garden Party. Here I wish to record my own appreciation of the help given by everyone. I shall not give a list of names, but I should like to mention two of the staff of de Havillands, Mr. Tom Grewar and his staff and Wing Commander C. A. Pike, for the co-operation given was unstinted and spontaneous. Another not to be passed over is Mr. Sutterly, the gardener. He transformed the surrounds, with his flowers, from those of a school into those of a Garden Party. My thanks to everyone.

Last month a Notice was included in the JOURNAL about the Reception to be held at 4 Hamilton Place, after the Wilbur Wright Memorial Lecture, to be delivered by Professor N. J. Hoff. There are two or three points about the Reception I wish to make. It is open to all members of the Society, and the guest may be a wife, a daughter, or a sweetheart, in brief, a lady. Perhaps this was not made clear in the Notice. Initially the number of guests has been limited to one, for the number which can be accommodated at 4 Hamilton Place is limited. However, if the supply of tickets exceeds the initial demand, tickets for more guests will become available to those who have asked for them. The words "buffet supper" are included in the announcement.

I hope that it will be possible to arrange space for dancing.

The Reception will serve the dual purpose of honouring the memory of the Wrights, and the Lecturer, Professor N. J. Hoff, and of initiating the Fourth Anglo-American Aeronautical Conference. The American Delegates will be at the Reception, and will be welcomed by everyone. Many are old friends and some will be new friends. I have received a list of delegates, and this list is longer than any previous one. I have arranged that one of the Committee rooms will be given up to the Ladies, both American and British, during the Conference, and can be used as a meeting place or lounge. The staff of the Society, not on duty at University College, will be prepared to assist the visitors in every way they can, while their menfolk are enjoying talk of a different breed at the Lecture Sessions.

The opening and final ceremonies of the Conference will be held in the Beveridge Hall, Senate House, University of London, and the Lectures in the Gymnasium and Eugenics Department of University College.

After the serious business of the 15th, 16th and 17th September the final fling—perhaps a prophetic word—will be held at the Dorchester Hotel, ending at approximately 2 a.m. This is only open to Delegates to the Conference and their ladies.

A. M. Ballantyne

Secretary

NOTICES

An annual sum of £250 is available for premium awards, usually 15 guineas each, for papers published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

President-Elect

Sir Sydney Camm, C.B.E., *Fellow*, Vice-President of the Society, has been selected President-elect for 1954 by the Council. He will take office at the Annual General Meeting to be held on 6th May 1954.

Associate Fellowship Examination

Home entries for the December 1953 Associate Fellowship Examination should be received by the Secretary not later than 31st August 1953. The lists for entries outside the United Kingdom have been closed.

News of Members

Air Chief Marshal Sir Roderic M. Hill (*Fellow*), Rector of the Imperial College of Science and Technology, has been elected Vice-Chancellor of London University for 1953/54.

Sir Frederick Handley Page (*Honorary Fellow*) succeeds Air Chief Marshal Sir Edgar Ludlow-Hewitt as Chairman of the Board of Governors, College of Aeronautics, Cranfield.

Mr. W. Barnard Faraday

Older Members of the Society will regret to hear of the death in June of Mr. W. Barnard Faraday, who was Secretary of the Society from 1917 to 1920.

Coronation Honours—Second List

K.B.E.

Air Marshal R. O. Jones, C.B., A.F.C., B.A., D.I.C. (*Fellow*).

C.B.E.

Group Captain Leslie Crocker (*Associate Fellow*).
Group Captain Bruce Robinson (*Associate Fellow*).

O.B.E.

Wing Commander R. P. Beamont, D.S.O., D.F.C. (*Associate*).

Awards to Members

Major D. Lester Gardner (*Honorary Fellow*), has been presented with the American Legion Medal of Merit for "his many years in actively aiding in the development of aviation, especially his founding of the Institute of the Aeronautical Sciences."

R. E. Hardingham (*Fellow*), Secretary and Chief Executive of the Air Registration Board, has been awarded the Society of Licensed Aircraft Engineers' Gold Badge for 1952, for his paper "Some of the Responsibilities and Problems of an Airworthiness Authority."

R. H. Nettell (*Associate*) has been given the Dorothy Spicer Memorial Award for 1953, for his paper "A Matter of Balance."

Fourth Anglo-American Aeronautical Conference
London 15th-17th September

At least 150 Delegates from the United States, a number of whom will be accompanied by their families, are expected to attend the Fourth Anglo-American Aeronautical Conference. The Technical Sessions of the Conference will be held at University College, Gower Street, London, W.C.1, on 15th, 16th and 17th September and the Delegates will attend the Reception which is to be held at 4 Hamilton Place, following the Wilbur Wright Memorial Lecture. This Reception is open to all members of the Society and a Special Notice and application form was enclosed with the July Journal.

The closing date for membership of the Conference was 31st July 1953 and we regret that the lists are now closed.

The following is the provisional order of Lectures and events arranged for the Conference.

Monday 14th September

6 p.m.	Wilbur Wright Memorial Lecture at the Royal Institution, 21 Albemarle Street.
8 p.m.	Reception at 4 Hamilton Place, W.1.

Tuesday 15th September

9.30 a.m.	Opening of Conference at the Beveridge Hall, University of London, Senate House.
11.30-1 p.m.	*Lectures* (1) "Structures for High Speed Aircraft" by H. L. Hibbard. *Chairman*: Sir William Farren. In The Eugenics Lecture Theatre.
	(2) "Power Plants for Helicopters" by Captain A. G. Forsyth. *Chairman*: Mr. C. J. McCarthy. In The Gymnasium.
3.0-4.30 p.m.	*Lectures* (3) "Basic Pre-Requisites Essential for Production" by Mr. R. A. Neale. In The Eugenics Lecture Theatre.
	(4) "Recent Advances in Circulation Control" by Mr. C. W. Perkins and Mr. D. C. Hazen. *Chairman*: Mr. A. A. Hall. In The Gymnasium.

Wednesday 16th September

9.30-11 a.m.	*Lectures* (5) "Structural Adhesives" by Dr. N. A. de Bruyne. In The Gymnasium.
11.30-1 p.m.	(6) "Aerodynamics of Compressor Blades" by Mr. H. Pearson. In The Gymnasium.
	(7) "Control of Flight" by Mr. P. R. Bassett. *Chairman*: Mr. G. R. Edwards. In The Eugenics Lecture Theatre.

2.30-4 p.m.	(8) "Aircraft De-Icing by Thermal Methods" by J. L. Orr, D. Fraser and J. H. Milsum. In The Eugenics Lecture Theatre. (9) "Some Factors Affecting Helicopter Design and Future Operations" by Mr. R. H. Miller. *Chairman*: Mr. E. Mensforth. In The Gymnasium.
4.30 p.m.	*Film* "Some Crash Fire Studies." In The Gymnasium.

Thursday 17th September

9.30-11 a.m.	*Lectures* (10) "Some Observations on the Problem of Fatigue" by Mr. R. V. Rhode. *Chairman*: Mr. B. S. Shenstone. In The Gymnasium.
11.30-1 p.m.	(11) "Pod Mountings of Turbo-Jet Engines" by Mr. G. S. Schairer. *Chairman*: Air Commodore F. R. Banks. In the Gymnasium.
2.30-4 p.m.	(12) "Introduction of the Comet into Service" by Mr. A. C. Campbell Orde. In The Gymnasium.
5.0-6 p.m.	*Conclusion* In The Beveridge Hall, University of London, Senate House.
7.30 p.m.-2 a.m.	Dinner-Dance, Dorchester Hotel, Park Lane, W.1.

Medals and Awards

The Council have made the following Awards. Some of the Medals will be presented at the Wilbur Wright Memorial Lecture, which is to be held on 14th September 1953 at the Royal Institution, 21 Albemarle Street, W.1.

The Society's Gold Medal.—The highest honour which the Society can confer for work of an outstanding nature in Aeronautics, awarded to:—

Mr. E. F. Relf, C.B.E., F.R.S., *Fellow*, for his outstanding contribution to Aeronautical Science over a period of many years.

The Society's Silver Medal.—For work of an outstanding nature in Aeronautics, awarded to:—

Mr. H. Grinsted, C.B.E., *Fellow*, for his outstanding work in Aeronautical Engineering.

The Society's Bronze Medal.—For work leading to an advance in Aeronautics, awarded to:—

Mr. L. Boddington, *Fellow*, Royal Aircraft Establishment, for his work on the development of Naval Aircraft.

The British Gold Medal.—For outstanding practical achievement leading to advancement in Aeronautics, awarded to:—

Mr. R. E. Bishop, C.B.E., *Fellow*, Chief Designer and Director, de Havilland Aircraft Co. Ltd., for his outstanding contribution to Aircraft Design.

The British Silver Medal.—For practical achievement leading to advancement in Aeronautics, awarded to:—

Mr. J. E. Gordon, Head of Structures Section, Chemistry Department, Royal Aircraft Establishment, for his excellent work in the sphere of Aircraft Structural Plastics.

The Wakefield Gold Medal.—Awarded Annually at the discretion of the Council, to the designer or inventor of any apparatus tending towards safety in flying, to:—

Mr. F. W. Meredith, *Fellow*, in charge of Research Department of Smiths Aircraft Instruments Ltd., for his work in the design of Automatic Pilots and Aircraft Instruments.

The George Taylor (of Australia) Gold Medal.—Awarded for the most valuable contribution read before, or received by, the Society on Aircraft Design, Manufacture or Operation, awarded to:—

Group Captain E. A. Whiteley, D.F.C., R.A.F., *Associate Fellow*, for his paper on "The Spacing of Aircraft Under High Density Approach Conditions" (August 1952 JOURNAL).

The Simms Gold Medal.—For the most valuable contribution read before, or received by, the Society on any subject allied to Aeronautics, awarded to:—

Major P. L. Teed, *Fellow*, Deputy Chief of Aeronautical Research and Development, Vickers-Armstrongs Ltd., for his paper on "Fatigue of Aircraft Materials with Special Reference to Micro-Structure" (June 1952 JOURNAL).

The R. P. Alston Memorial Prize.—For practical achievement associated with the flight testing of aircraft, awarded to:—

Captain A. M. A. Majendie, Flight Captain, B.O.A.C., for his work in connection with the introduction of jet-propelled aircraft into civil operation.

The Herbert Akroyd Stuart Memorial Prize.—For the most valuable contribution read before, or received by, the Society on Applied Thermodynamics, awarded to:—

Mr. J. E. Walker, *Associate Fellow*, Chief Power Plant Designer, de Havilland Aircraft Co. Ltd., for his paper on "Fuel Systems for Turbine-driven Aircraft" (September 1952 JOURNAL).

The Edward Busk Memorial Prize.—For the most valuable contribution read before, or received by, the Society on Applied Aerodynamics, awarded to:—

Mr. C. P. Plantin, *Associate Fellow*, for his paper on "The Technique of Resonance Testing and Flutter Calculations as Applied to Fighter Aircraft Design" (February 1952 JOURNAL).

The Pilcher Memorial Prize.—For the most valuable paper read by a Graduate or Student during the previous year at any meeting of the Society or its Branches, awarded to:—

Mr. P. H. Southwell, *Graduate*, for his paper on "Aircraft in Agriculture" (January 1952 JOURNAL).

The Usborn Memorial Prize.—For the best contribution to the Society's publications written by a Graduate or Student on some subject of a technical nature in connection with aeronautics, awarded to:—

Mr. E. M. Dowlen, *Graduate*, for his paper on "A Shortened Method for Calculation of Aerofoil Profile Drag" (February 1952 JOURNAL).

The Orville Wright Prize.—For the best contribution received for publication in *The Aeronautical Quarterly* of the Society on some subject of a technical nature in connection with Aeronautics, awarded to:—

Professor W. A. Mair, *Associate Fellow*, for his paper on "The Sensitivity and Range Required in a Toepler Schlieren Apparatus for Photography of High Speed Air Flow" (Vol. IV, August 1952).

The Branch Prize.—For the best paper on an Aeronautical subject read before the Branches during the previous lecture session, awarded to:—

Mr. C. Dykes, *Associate Fellow*, for his paper on "Some Operating Problems of Future Transport Aircraft."

The E.J.N. Archbold Memorial Prize.—Awarded annually to the candidate obtaining the highest marks in the Technological Examination of the City and Guilds Examination in Aeronautical subjects to:—

Peter Frederick Jowett.

Diary

LONDON

August 26th

GRADUATES' AND STUDENTS' SECTION. All-day visit to Royal Aircraft Establishment. *See* separate notice.

September 14th

41st Wilbur Wright Memorial Lecture—Structures—Buckling and Instability. Professor N. J. Hoff. Royal Institution, Albemarle Street, London, W.1, at 6 p.m.

RECEPTION.—4 Hamilton Place, W.1, following the Wilbur Wright Memorial Lecture. (*See* Leaflet enclosed with July JOURNAL.)

September 15th-17th

Fourth Anglo-American Aeronautical Conference. University College, Gower Street, W.C.1. *Delegates only.*

September 17th

DINNER DANCE—Dorchester Hotel. 7.30 p.m.

September 22nd

GRADUATES' AND STUDENTS' SECTION. Visit to Bankside Power Station. *See* separate notice.

BRANCHES

August 31st

Halton.—General Meeting of Junior Members. The Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

September 7th

Halton.—Branch Night. The Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

September 21st

Halton.—Films. The Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

September 28th

Halton.—Lecture—Fluid Control Waves. S. G. Shand. The Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

October 5th

Glasgow.—Helicopter Design Problems. A. H. Yates. Royal Technical College. 7.30 p.m.

November 3rd

Glasgow.—"Any Questions." St. Enoch Hotel. 7.30 p.m.

December 3rd

Glasgow.—The Development of Modern Aircraft. A. W. Babister, Royal Technical College. 7.30 p.m.

MEMBERS' NEW APPOINTMENTS

W. W. GREENFIELD (*Fellow*) has been appointed assistant chief designer to take charge of the new London Design Office of Blackburn and General Aircraft Ltd.

G. JACKSON (*Graduate*) has been appointed a lecturer in the Department of Aeronautics at the Imperial College of Science and Technology, as from 1st September 1953.

Group Captain R. A. B. STONE (*Associate Fellow*) has recently joined the Research and Development Division of the Cement and Concrete Association.

GRADUATES' AND STUDENTS' SECTION

An all-day visit has been arranged to the **Royal Aircraft Establishment, Farnborough, on Wednesday 26th August 1953,** from 10.30 a.m. to 4.30 p.m. Lunch will be available. Visitors will see the wind tunnels, structural and engine test rigs, and the flight test department.

Applications should be sent to the Honorary Visits Secretary, C. B. Redgate, 83 Wandle Road, Morden, Surrey, and members are asked to state their full name, **grade of membership of the Society and whether they are British Subjects.**

A visit has also been arranged to the **Bankside Power Station** for Tuesday 22nd September 1953, at 6.30 p.m. Applications should be sent as soon as possible to the Hon. Visits Secretary, C. B. Redgate, stating full name, **nationality,** and grade of membership of the Society.

JOURNAL PREMIUM AWARDS

The following Premium Awards, each for fifteen guineas, have been awarded by the Council for papers published in the JOURNAL in 1952:—

Mr. C. F. Joy, A.F.R.Ae.S., for his paper on "Power Controls in Aircraft" (January 1952 JOURNAL).

Mr. L. E. Bunnett, A.F.R.Ae.S., for his paper on "Production Research on Aircraft" (March 1952 JOURNAL).

Mr. B. A. Hunn, B.Sc. (*Companion*), for his paper on "A Method of Estimating the Loading on an Elastic Airframe" (April 1952 JOURNAL).

Mr. P. W. Brooks, B.Sc., A.C.G.I., A.F.R.Ae.S., for his paper on "Problems of Short Haul Air Transport" (June 1952 JOURNAL).

Mr. K. G. Hancock, B.Sc.Tech., A.F.R.Ae.S., and Mr. P. Person, M.A., A.F.R.Ae.S., for their paper on "Power Steering for Aircraft" (July 1952 JOURNAL).

Mr. J. W. Blinkhorn, B.Sc., A.F.R.Ae.S., for his paper on "Loads on Multi-wheel Undercarriages During Ground Manœuvring and Take-off" (July 1952 JOURNAL).

Mr. C. H. Jackson, B.Sc., A.F.R.Ae.S., for his paper on "Some Notes on Aircraft Overhaul and Maintenance" (August 1952 JOURNAL).

Mr. D. G. Ashwell, M.A., for his paper on "The Stability in Bending of Slightly Corrugated Plates" (October 1952 JOURNAL).

Mr. Keri Williams, B.Sc., A.F.R.Ae.S., for his paper on "Fatigue Life of Wing Components for Civil Aircraft (November 1952 JOURNAL).

Group Captain G. M. Buxton, O.B.E., M.A., A.F.R.Ae.S., for his paper on "Problems of Servicing and Reliability" (December 1952 JOURNAL).

SYMPOSIUM ON TESTING AND STRESS GRADING OF TIMBER

A symposium on this subject will be held on Tuesday 22nd September 1953 at the Institution of Civil Engineers, Great George Street, London, S.W.1, when the following four papers will be presented:—

10.00 a.m. "Methods of Test of Small Clear Specimens" by F. H. Armstrong (Forest Products Research Laboratory).

11.30 a.m. "The Testing of Structural Components and Structural Units" by J. G. Sunbury (Forest Products Laboratory).

2.00 p.m. "The Mechanical Testing of Sawed Timbers and Application of Data to Stress Grading" by W. J. Smith (Forest Products Laboratory, Canada).

3.30 p.m. "Strength Studies of Timber in the Development of Structural Timber Grades" (Forest Products Laboratory, U.S.A.).

The symposium is being sponsored by the Incorporated Association of Architects and Surveyors, 75 Eaton Place, London, S.W.1, to whom Members should write if they wish to attend the meeting.

Advance copies of each of the four papers will be available from the Incorporated Association of Architects and Surveyors, price 1s. 6d.

ACKNOWLEDGMENT

The Council acknowledge with grateful thanks the return of back numbers of the JOURNAL from W. L. Amer, Esq., *Associate Fellow.*

Associate Fellowship Examination Results

The following are the results of the Associate Fellowship Examinations held in May 1953:—

Part I—Home

K. Bennett, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Materials and Theory of Structures I; W. Blydenstein, Applied Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Materials and Theory of Structures I, Theory of Machines; K. J. Bullock, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Materials and Theory of Structures I.

S. R. Cann, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Materials I; M. Chandra, Strength of Materials and Theory of Structures I, Theory of Machines.

J. W. Drife, Aerodynamics I.

J. W. Gardner, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Materials and Theory of Structures I; M. J. Goldsmith, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Materials and Theory of Structures I.

L. A. Hall, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Materials I; B. E. Hart, Aerodynamics I, Strength of Materials and Theory of Structures I; K. H. Hφie, Applied Mathematics, Strength of Materials and Theory of Structures I, Theory of Machines.

M. H. Irwin, Applied Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Materials and Theory of Structures I, Theory of Prime Movers and Fuels.

D. C. Kohli, Strength of Materials and Theory of Structures I, Theory of Machines.

T. C. Lee, Strength of Materials and Theory of Structures I; J. F. Leigh, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Materials and Theory of Structures I.

J. Macnaughton, Pure Mathematics; B. A. W. Martin, Strength of Materials and Theory of Structures I, Theory of Prime Movers and Fuels.

D. J. Richardson, Strength of Materials and Theory of Structures I.

R. P. Stanford, Properties of Matter, Heat, Light and Sound; M. A. Sutherland, Pure Mathematics, Strength of Materials and Theory of Structures I, Theory of Machines.

S. W. Tubbs, Aerodynamics I, Strength of Materials and Theory of Structures I.

B. S. Ward, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Materials and Theory of Structures I; D. Wilkinson, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Materials and Theory of Structures I; J. W. Wisdom, Properties of Matter, Heat, Light and Sound.

Part I—Abroad

A. Subrahmanyam (Bangalore, India), Aerodynamics I.

Part II—Home

J. A. F. Allan, Meteorology, Engineering Economics; J. Allcroft, Aerodynamics II; R. Ashford, Aerodynamics II.

D. R. Barham, Strength of Materials and Theory of Structures II; T. S. Beddoes, Aerodynamics II; D. G. A. Bridgnell, Strength of Materials and Theory of Structures II; D. R. Brodie, Strength of Materials and Theory of Structures II; W. R. Bryce, Strength of Materials and Theory of Structures II; P. H. F. Burton, Aircraft Materials, Engineering Economics.

K. G. Draper, Strength of Materials and Theory of Structures II.

P. J. Farmer, Engineering Economics; R. P. Francis, Strength of Materials and Theory of Structures II.

J. F. G. Hart, Strength of Materials and Theory of Structures II; I. Harwood, Aircraft Design; A. J. Heath, Strength of Materials and Theory of Structures II; E. A. R. Humpston, Aerodynamics II.

M. E. King, Aircraft Design.

R. Lewis, Strength of Materials and Theory of Structures II.

C. L. Munro, Aircraft Materials, Engineering Economics.

J. M. O'Connell, Strength of Materials and Theory of Structures II; C. V. Olver, Aircraft Design.

A. G. Rogers, Aircraft Design; J. Rye, Aircraft Design.

R. D. Saha, Aircraft Materials, Engineering Economics.

J. D. Watkins, Strength of Materials and Theory of Structures II, Aircraft Design.

Part II—Provincial

L. A. Goodson, Strength of Materials and Theory of Structures II.

Part II—Abroad

J. M. Jehin (Marche-en-Famenne, Belgium), Engine Design.

A. Subrahmanyam (Bangalore, India), Aircraft Design.

B. J. Van de Water (Sydney, Australia), Aerodynamics II.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Robert Henry Watson Annenberg (*from Graduate*)
Ernest Norman Beswick
Thomas Walter Falconer Brown
John Burton Harris Campbell (*from Graduate*)
Kenneth William Campbell (*from Graduate*)
Stanley Edward Clotworthy
Douglas Ronald James Colpus (*from Graduate*)
Robert Joseph Evans (*from Associate*)
Kenneth Oliver Grant
Raoul Hafner
Derek George Harris (*from Graduate*)
Jesse Hart (*from Associate*)
George Thomas Hayes (*from Graduate*)
David King
Leslie Alan Lee
Alastair McKay (*from Graduate*)
James Meadows (*from Graduate*)
James Roland Miller (*from Graduate*)
Denis Edward Williams (*from Graduate*)
Ernest Wilks (*from Graduate*)
Richard Phillip Wade (*from Graduate*)
Ronald George Stantone (*from Graduate*)
Leonard Thomas Smith
Colin Graham Saunders
Leslie Geoffrey St. Leger (*from Graduate*)
Eric William Evan Rogers Owers (*from Graduate*)
Donald William Bernard
Edward James Nicholl
Robert Waudby Morris (*from Graduate*)

Associates

Donald Barlow
Laurie Arthur Thomas Best
Ronald Frederick Jupp
John Hamilton Malcolm
Derek Moore (*from Student*)
John Rushton
Andrew Montague West
Ernest Alfred Wren

Graduates

Derek George Brooks
Thomas Bruce Cairns Davidson
Roy Vivian Fowkes
Bernard James Hulley
John Barry Knight
Ronald Mackenzie
Hugh Christopher Henry Mereweather (*from Student*)
John Henry Paul
Allan John Saldanha
Geoffrey Edmund Salt (*from Student*)
Rodney Shaw
Anthony John Spurgin (*from Student*)
Albert Arthur Weeks
Ronald Sidney Williams
Donald Rouston Willmer

Students

David Brown
Donald Stanley Buckle
Jack Burnham
John Churchill
Judith Anne Clarkson
Derek Geoffrey Eastwell
Keith Hind
Raymond Lewis
Derek Leslie Norris
John Payne
Frank William Henry Ponsford
George Stevens
Frank James Trufelli
Frank Webber
Basil Charles Whorwood

Companions

Ian Robert Liddell
Fowke Jean Andre Mangeot

Journal Binding

Self-Binder Cases

Self-Binder cases of the "Easibind" type are available from the offices of the Society. These binders are for members who do not have their Journals permanently bound, or who wish to keep their Journals together during the year for binding later.

These cases will hold 12 Journals which are kept in place by means of flexible steel wires. Journals can be inserted or withdrawn easily without damage, so preserving the contents for permanent binding later. The Journals will open flat at any page.

The binder is strongly made in durable dark blue leather cloth on stiff board covers and has gold lettering on the spine. The year is not blocked on the spine but there is a panel on which members who wish to use the binder as a permanent case can put the date.

The cost is 11s. 6d. each including postage and packing for either the size to fit 1952 and previous Journals, or for the size to fit the Journal from January 1953, which has been increased in size. Orders and remittances should be sent direct to the Secretary at the Offices of the Society and it is *important to state whether the old size or new size is required.*

Permanent Binding

There is no increase in the price of permanent binding of Journals. The prices are:—

1952 Volume (including packing and postage) 16s. 0d.
Previous Volumes (including packing and postage) 18s. 0d.

Journals, *with a note of the name and address of the sender,* should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Changes of Address

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 57 AUGUST 1953 NUMBER 512

Ninth British Commonwealth and Empire Lecture

Some Problems in the Development of Air Transport in West Africa

by

SIR HUBERT WALKER, C.B.E., M.I.C.E.

The Ninth British Commonwealth and Empire Lecture was given by Sir Hubert E. Walker, C.B.E., on 11th June 1953 at the Royal Institution, 21 Albemarle Street, London, W.1. Sir William S. Farren, C.B., M.B.E., F.R.S., F.R.Ae.S., President of the Society, presided.

Introducing the Lecturer, the President said that he began by walking over West Africa, then rode over it, then motored and finished by flying. After serving in the 1914-1918 War, Sir Hubert joined the Public Works Department, Nigeria, in 1919 as an engineer, becoming Superintendent in 1929, Deputy Director in 1935 and Director in 1944. When he retired in 1948 he was also Controller of Civil Aviation, Nigeria. He was appointed an O.B.E. in 1935, C.B.E. in 1943 and was created a Knight in 1947. He was Chairman of West African Airways Corporation.

WEST AFRICA, particularly British West Africa, has been one of the last areas to be opened up to Air Transport and because of physical and financial difficulties, progress has been slower than in most other parts of the Empire.

General Description

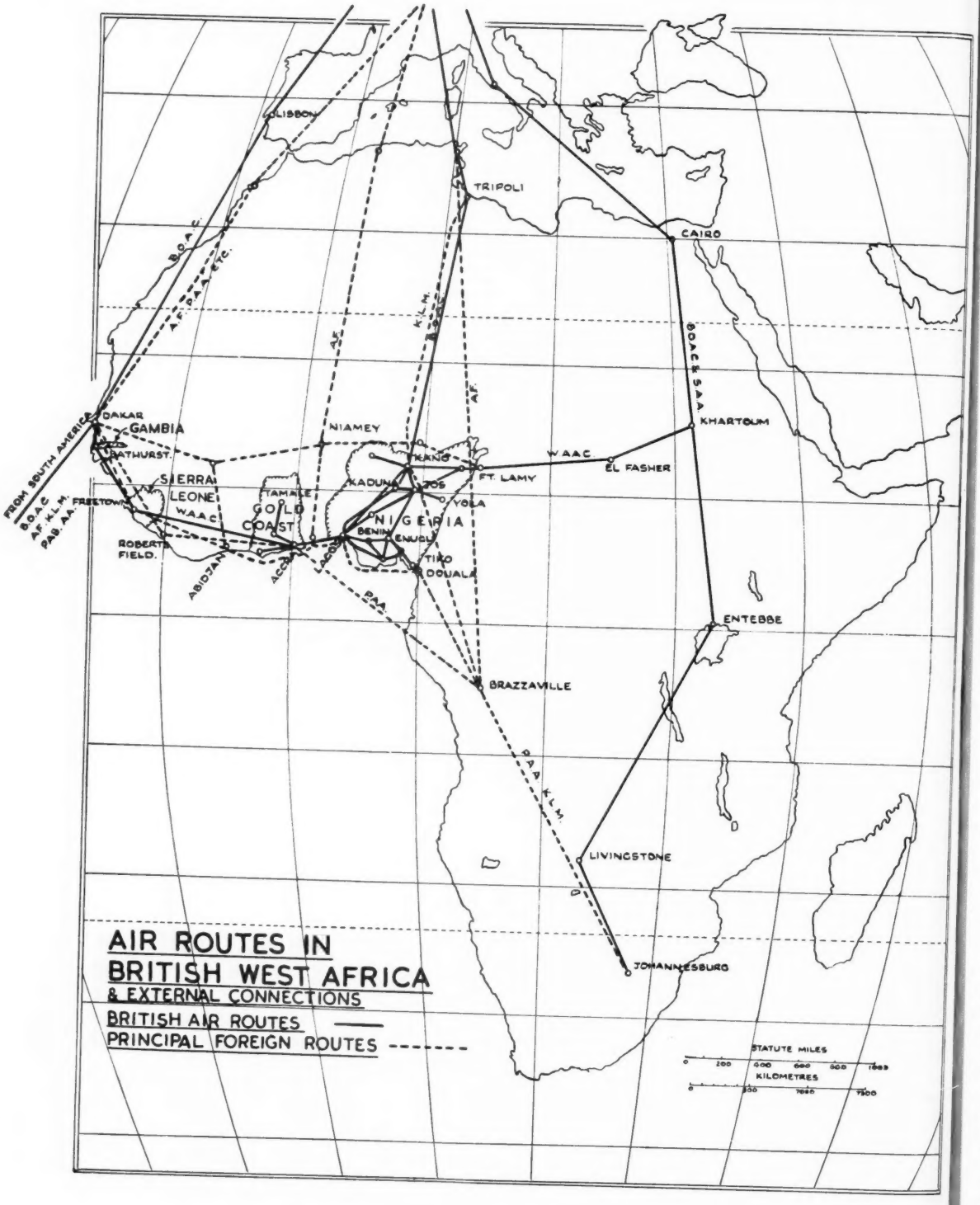
As West Africa, even today, is not very well known in other parts of the Empire, it will be useful to give a brief description of the territory and the early history of aviation there before dealing with the special problems encountered in the development of air transport.

While the particular territories dealt with in this lecture are the four British West African Colonies and Protectorates of the Gambia, Sierra Leone, the Gold Coast and Nigeria, it will be necessary, from time to time, to make passing reference to the adjacent French territories and even to the Anglo-Egyptian Sudan.

The four British territories, unlike those in East Africa, are not contiguous but each is surrounded on the land side by the intervening French territories of Senegal, Guinea, Ivory Coast, Dahomey, Volta, Niger, Chad and the Cameroons. The largest of the British territories is Nigeria with an area of 372,674 square miles and a population of probably 30,000,000; the census results will not be known until the end of this year, but this figure seems a reasonable forecast. The next largest is the Gold Coast with 91,690 square miles and a population of 4,500,000. Sierra Leone and the Gambia are much smaller with areas of 28,000 square miles and 4,000 square miles, and populations of 2,000,000 and 270,000 respectively. The total area is thus about 496,500 square miles and the population approximately 37,000,000. The adjoining territories of French West Africa have an area of 1,800,000 square miles and a population of 16,000,000. Although these figures are large and it might be expected that air transport would develop rapidly, the British territories are comparatively poor in terms of wealth per head. An indication of individual means is given by the current year's Nigerian Government budget of £47,000,000, equivalent to about 30/- per head, and the Gold Coast Revenue of £20,000,000 or 88/- per head.

Geography

Along the coastal belt the country is covered with tropical rain forest and, except for a few places such as Freetown in Sierra Leone, and the vicinity of Accra, the actual coast is bordered by swamps, while on the beaches a heavy surf caused by waves originating from storms in the South Atlantic, probably near the Falkland Islands, pounds the sand throughout the year. Inland, the country rises gradually, in places to 2,000 ft. above sea level, the forest giving way to orchard bush until the watershed between the coast rivers and the valleys of the Niger and Benue is reached; it then falls away gently to those rivers rising again beyond them to between 1,500 and 2,000 ft. There are few high areas,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PAN AA.
AIR ROUTES IN
BRITISH WEST AFRICA
& EXTERNAL CONNECTIONS
BRITISH AIR ROUTES
PRINCIPAL FOREIGN ROUTES
STATUTE MILES
KILOMETRES

the most important being the mountains to the north-east of Sierra Leone with peaks up to 6,000 ft., the Bauchi Plateau in Nigeria at a level of 4,000 ft. and peaks up to 6,000 ft. with the aerodrome at Jos at 4,250 ft., the Cameroon Mountain in the extreme south-east of Nigeria at 13,370 ft. and, just to the south of the route between Kano and Khartoum, the Marra Mountains near the Sundan frontier going up to 10,000 ft. Jos is the only aerodrome at any considerable altitude. True desert conditions do not occur until well north of the line Dakar-Kano-Khartoum, except in the Sudan between El Fasher and Khartoum.

Climate

In general, the climatic conditions consist of fairly well defined wet and dry seasons, the rains starting about May and finishing in October with the remainder of the year comparatively dry. On the coast, temperatures above 95° are rarely experienced, but so are temperatures below about 75°, and humidity is high. Inland, the humidity decreases and higher maximum and lower minimum temperatures are general, with a considerable seasonal range. Rainfall varies from around 70 to 100 inches of rain on the coast, to 20 to 40 inches in the latitude of Kano. During the rains electric storms are common, with almost continuous thunder and lightning, and winds of 40 and 50 m.p.h., but gusts of 100 m.p.h. have been recorded. They are rarely of long duration, nor do they cover a large area. The clouds reach up to 20,000 ft. Another type of storm is the line squall which on occasion extends along a front of over 100 miles; these also are of short duration, but extend to a great height. In the dry season the principal trouble is the Harmattan storm, which is an east wind heavily laden with desert dust, probably from the Tibesti area, which at times reduces visibility to a few yards. These storms last for about three days with varying degrees of hinderance to visibility. Morning mists or hill fogs occur on rising ground near the coast in the early mornings and cause delays to air services. Round mid-day and in the early afternoon there is considerable turbulence at low altitudes.

Historical

Historically, the effective beginning of civil air transport in British West Africa was the Imperial Airways service from Khartoum to Kano which was inaugurated in January 1936, using D.H. 86s. Before this date there had been a certain amount of flying between Khartoum and Nigeria by the R.A.F., and in Nigeria and the Gold Coast by private individuals, and the French were operating regular services from their own territories to North Africa and Paris. The earliest R.A.F. flight which can be recalled was in 1925 by the flight stationed at Khartoum using, it is believed, Vickers Victorias. This exercise became an annual event and many stations in Northern Nigeria were visited; later it was extended as far as Lagos.

There were several private enthusiasts who flew small aircraft with varying degrees of success, notably a Mr. Carpenter at Kano round 1930 and Col. Rattray on the Gold Coast. The owner of a seaplane ran a few trial trips between Lagos and Warri, and another with a small Junkers flew round Northern Nigeria giving flights at £1 a passenger. The reports from all these experiences emphasised the difficulties and the general view was that while land-based aircraft could be used in the more northerly areas, in the coastal area seaplanes only would be practicable. One R.A.F. report in the early thirties caused some consternation by recommending emergency landing strips at intervals of 50 miles or less.

The real start of Civil Air Transport in British West Africa was, however, the Imperial Airways once-weekly service from the United Kingdom via Khartoum to Maiduguri and Kano, in January 1936. This service was extended later in that year to Lagos, with stops at Kaduna, Minna and Oshogbo, and shortly afterwards to Accra and Takoradi in the Gold Coast.

A seaplane service was also operated by Imperial Airways, in conjunction with Elder Dempsters, between Freetown and Bathurst, but was rather spasmodic. In 1937 the Lufthansa started operating a service to South America involving a stop at Bathurst, where the Company put down an aerodrome with a steel grid surface and stationed a ship for the trans-Atlantic flight. The French also proceeded with the development of their services, but did not land in British territory.

This once-weekly Imperial Airways Service, carrying 18 passengers, met the primary need for air connections with the U.K. for the next four years. In this connection it should be borne in mind that external traffic has always been, and still is, preponderently to Europe ever since the 15th century when the Portuguese under Henry the Navigator sailed their ships round Cape Verde and into the Bight of Benin, and this remained the normal avenue of communication between the Coast of West Africa and the outside world. From Tripoli there were caravan routes across the Sahara to Kano and the other great markets in a chain stretching from Khartoum to Dakar, but they did not penetrate farther south. In fact, it was not until 1905 that one of the principal Tripoli traders in Kano, Nasuf, was induced to take a small caravan of 18 oxen by the newly constructed road southwards from Kano to Zungeru and eventually reached Lagos, whence he returned to Tripoli via England. It was reported that on his arrival in Tripoli the news of his adventurous journey from the north coast of Africa to the Bight of Benin created a considerable sensation. It is interesting to note that the cost of transport by caravan from Tripoli to Kano at the beginning of this century was estimated at £27 a ton while the present-day air freight rate is £25. In earlier times, it is reported that at Timbuctoo salt and gold were exchanged, ounce for ounce.

There has always been considerable pilgrim traffic across to Khartoum and Jedda, but traffic to East and South Africa was non-existent and is still negligible. Although the primary object of the Imperial Airways service was connection with the U.K. the length of the route within the Gold Coast and Nigeria, and the number of stopping places—*i.e.* Takoradi, Accra, Lagos

Oshogbo, Minna, Kaduna, Kano, Maiduguri—enabled it to provide also, to a limited extent, for local internal traffic. Nevertheless, the need for internal services at some future date was foreseen and, as the first requirement would be aerodromes, schemes were prepared for a system of aerodromes suitably sited for this purpose.

The early stages of the war affected West Africa very little from the aviation point of view; the weekly service to the U.K. continued and the French carried on with their services from France to Cotonu and Dakar. The Lufthansa service to Bathurst was, of course, discontinued. With the collapse of France and entry of Italy into the war the picture changed completely and West Africa became the scene of extensive and feverish activity. Bathurst and Freetown became of the greatest importance and the Air Ministry put in hand the construction of major aerodromes at both places. The U.S.A.A.F. proceeded with the construction of aerodromes in Liberia at Robertsfield, Harper, and at Fishermans Lake, which was also a flying boat base.

In Nigeria and the Gold Coast this phenomenal increase in traffic led to rapid improvement in the principal aerodromes and construction of numbers of additional subsidiary landing grounds, nearly all of which were to prove extremely useful in the post-war development of civil aviation.

The French West African territories having declared for Vichy were out of the picture; but in Chad, which is included in French Equatorial Africa, Governor Eboué (an African) declared for de Gaulle, thus making safe the route from Kano to the Anglo-Egyptian Sudan. Considerable assistance was rendered by Nigeria to Chad in improving and providing bituminous surfacing to the aerodromes at Fort Lamy and Fort Archambault which were on this route.

The only development of civil aviation was that when the Mediterranean was virtually closed, the B.O.A.C. services available to civilian traffic were re-routed via Lisbon, Bathurst and Freetown to Accra and Lagos. As the services via Kano to Khartoum were still operated, this re-routing gave a real trans-African route from Bathurst to Khartoum. Although little civil development was possible, the question of post-war development of civil aviation was not neglected and in 1944 Lord Swinton, the Resident Minister in West Africa, appointed a committee under the Chairmanship of Mr. F. H. Sandford (now Sir Folliott Sandford). This committee collected a great deal of valuable information which, although mainly about external traffic, was also most useful on the problem of local services.

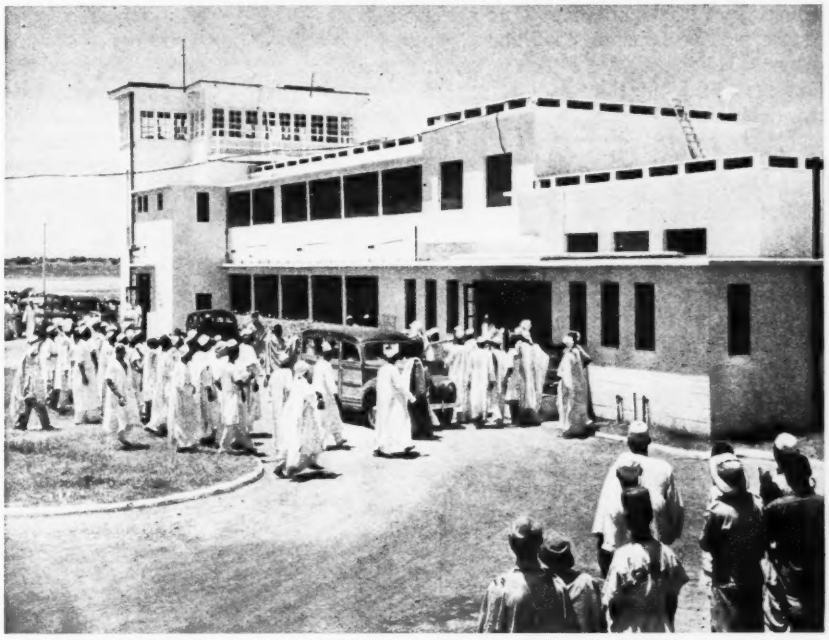
Later in the same year arrangements were made with R.A.F. Transport Command to operate an internal service in Nigeria, available to the public. Dakotas were used and, to obtain the maximum facilities with the limited flying hours available, the service operated in a circular route Lagos, Port Harcourt, Enugu, Jos, Kano, Lagos twice-weekly in each direction. It was known locally as the "Bush Service." At Lagos it connected with a twice-weekly B.O.A.C. service to the United Kingdom, via Bathurst and Lisbon. It was eventually withdrawn in May 1946.

Meantime active consideration was given to the whole problem of air services within West Africa. A survey was made by the Ministry of Civil Aviation in 1945 and during the year much advice was received from the R.A.F. and B.O.A.C., but the solution to the problem was still not clear. What was wanted was known, but not how to get it. In September 1945 arrangements were made for a visit by the Colonial Office Adviser on Civil Aviation, who reported in January 1946. This report was considered by the West African Council at a meeting in Accra in February under the presidency of the Secretary of State for the Colonies, Lord Hall, and it was decided to refer the matter to a small committee. This committee reported the next day and recommended the formation of a West African Air Transport Authority and also recommended the formation of a Corporation, to be financed by the four colonial governments and entrusted with the duty of operating and developing air transport within and between the territories. This recommendation was accepted, and the West African Airways Corporation was created by an Order in Council dated 16th May 1946.

An early problem was presented by the withdrawal of the R.A.F. "Bush Service" in May 1946 and, as this was long before the Corporation could hope to obtain any aircraft of its own, or recruit staff, and as it was considered necessary to preserve a skeleton internal service in Nigeria, arrangements were made with the B.O.A.C. to run a service on a charter basis on the route Lagos, Port Harcourt, Jos, Kano, twice-weekly in each direction. This service operated until December 1947 when the West African Corporation was able to start functioning with its own aircraft. In September 1947 the B.O.A.C. re-routed their main line to West Africa from London via Tripoli and Kano to Accra and Lagos, but continued to operate a local service from Lagos and Accra to Freetown and Bathurst, connecting this with the London—South American service of British South American Airways. The saving in time was considerable, and Lagos and Accra were brought to within 24 hours of London, a great difference between the six days on the pre-war route via Khartoum and the three days of the war-time route via Bathurst and Lisbon.

From December 1947, West African Airways has gradually extended its services in Nigeria and the Gold Coast, using Doves. Although local services in British Africa have gradually developed until today the route mileage is 8,677 and the total aircraft miles flown annually some 2,250,000, carrying some 57,000 passengers, from the financial standpoint this is small in comparison with the external traffic, nearly all of which is to the U.K. by B.O.A.C. carrying 17,000 passengers annually; the average fare paid by the internal passengers is only a little over £10 each against about £100 each by the external passengers.

In the French territory where the European population is many times larger than in British West Africa, although the total population is only about half, development of air transport has in general been earlier



Terminal building, Kano Airport.

than in the British territories and there are three main line operators connecting with France. Air France, Union Aeromaritime de Transport (U.A.T.) and Compagnie des Transports Aériens Intercontinentaux (T.A.I.), operate four routes across the Sahara, two from Algiers and two via Casablanca, and one round the coast. Against the background of this general picture, the more important problems can now be described.

Aerodrome Siting

The first problem, as far as West Africa was concerned, was the provision of aerodromes since the question of suitable types of aircraft was initially a problem for someone else. Consideration was first given to this problem around 1930/31, but it was not necessary to take definite action until 1935, when Imperial Airways proposed to start the service via Khartoum to Lagos and Accra and a representative of the Air Ministry visited Nigeria and inspected the sites selected for the chain of aerodromes and landing grounds. Runways, as opposed to area grounds, were just coming into favour at that time and the decision was made to adopt runway design for the aerodromes on the main trunk routes. Great importance was paid at this time to cross-winds and the original recommendations favoured at least three and sometimes more runways; in fact, some of the early plans looked rather like a Union Jack. However, as time was short and funds limited, it was decided to start with the construction at each landing ground of one main runway of 1,000 yds., extendable later to 1,500 yds., in the direction of the prevailing wind, and a secondary runway of 800 yds. for use when there was a strong cross-wind on the main runway. The construction of a third, or even fourth, runway was left until experience could be gained in actual use.

Another reason for this course was, that it was only at the principal stations, such as Lagos and Accra, that there were trained meteorological observers, so that while a reasonably accurate wind-chart showing directions could be prepared for most stations, the strength of winds was not so certain. Records referred to the Beaufort scale and there was some reason to suppose that the natural phenomena, which form the basis for this scale, occurred at lower velocities in West Africa than in Europe. From 1932 to 1935 some investigation on wind velocities had been made in Northern Nigeria in connection with the use of windmills and these showed that average wind speeds were below 7 miles per hour. As an example, at Sokoto the daily average only exceeded 7 miles per hour on two occasions, *i.e.* in July 1934 and June 1935, and even then was only 7·13 and 7·39 m.p.h. respectively.

The reduction in wind pressure due to high temperatures and elevation above sea level had also to be taken into account. This adjustment is considerable, as at 2,000 ft. above sea level and a temperature of 95°F. the wind power is only 86 per cent. of that at sea level with a temperature of 50°F. While temperature and elevation thus reduced the need for cross-runways, they indicated the necessity for increasing the length of runways, especially for take-off when the reduction in the efficiency of internal combustion engines, due to temperature and elevation, also adds to the length of runway required.

The decision to limit construction to one main runway and a shorter secondary runway was fully justified by subsequent experience for, as time went on, it was found that the secondary runways were used to a

decreasing extent and that pilots preferred to use the longer runway under all conditions. At only one aerodrome, Maiduguri, were three runways constructed, and even there the third rapidly became merely a taxi track. In fact, the present-day tendency is towards the single runway landing ground.

Runway Length

Although only 1,000 yds. was specified initially, 1,200 yds. was provided where this could be done at only small additional expense, and these lengths proved fully adequate for some years. In fact, it is interesting that, because the Imperial Airways service started shortly after notice was received, it was impossible to construct aerodromes at Maiduguri and Kano in the time, and for the first few months the D.H. 86s used the polo grounds at these stations. As the length of the diagonal across a polo ground is barely 400 yds., the author was reminded very much of the first aerodrome on the construction of which he was employed in 1915, which was a 400 yds. square.

These lengths for runways sufficed until 1941, when the R.A.F. reinforcement route to the Middle East was started and little difficulty was experienced by the Colonial Public Works Dept. in extending the runways of the principal aerodromes, first to 1,800 yds. and then to 2,000 yds., except at Lagos and Takoradi. At Lagos the site was mostly a swamp with some 70 ft. depth of mud, and the runway was constructed on sand dredged from the harbour and pumped onto the site. In 1942 another site was selected on the mainland at Ikeja and work was started. At first Ikeja was intended only as an emergency strip but Lord Swinton, the Resident Minister in West Africa, after hearing the difficulties of maintaining Apapa, ordered Ikeja to be extended to a full-scale aerodrome.

At Bathurst in the Gambia the landing ground constructed by the Lufthansa, using a steel grid, very quickly became inadequate in length and in 1940 another site was selected at Yundum, the present aerodrome. The site was flat and presented no difficulty, but the soil was a very light sandy loam and, as speed was important, pierced steel planking was used for surfacing. It was not, however, fully realised at the time that this particular soil required some measure of compaction, even under pierced steel planking, with the result that the original runway developed waviness to the extent of becoming unusable. A parallel strip was therefore consolidated and further steel planking put down. This runway is in excellent condition to this day and requires little maintenance. At first these steel runways were kept carefully weeded, but it was found later that, if the growth of grass through the holes in the planking were encouraged, the rattling sound caused by undercarriage wheels was eliminated to a great extent.

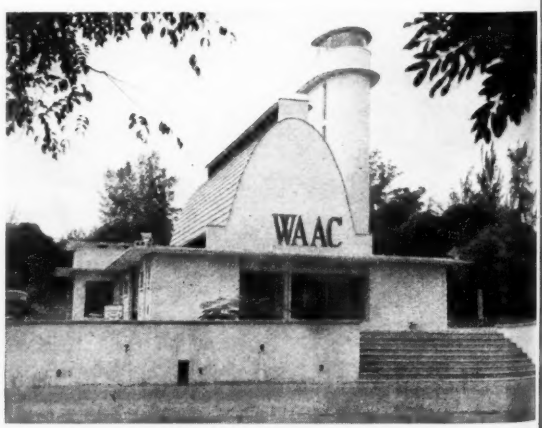
At Freetown, Sierra Leone, the first aerodrome was fairly near the town at Hastings, but owing to the proximity of the mountain, using it was rather like landing up a spout. Another site was selected some 17 miles from the town, at Waterloo, but here, because of the heavy earthworks involved, much of the runway was on excavated ground and troubles similar to those at Takoradi were experienced. A little later, the R.A.F. constructed a third aerodrome at Lungi, on the opposite side of the harbour, and when the troubles at Waterloo in 1947 became serious it was decided to abandon Waterloo and adopt Lungi as the civil airport.

Of the 36 aerodromes constructed in British West Africa only one in Nigeria and two in Sierra Leone have been abandoned for reasons of unsuitability of the site. A further 10 of those constructed during the war for military purposes are not regularly used, pending the development of traffic, leaving 23 in regular use by scheduled services.

Bearing Values of Runways

For the first years up to 1941, the bearing values of runway surfaces in relation to weight of aircraft was not a serious problem. A soil mechanics laboratory had been established in Lagos in 1930 by the Nigerian Public Works Dept., where mechanical analyses of soil were made. Much work had been done on the investigation of the strength and wearing value of materials

Standard Nigerian control tower, Port Harcourt.



Booking office, Enugu.

for surfacing and base courses for roadwork, and the value of lateritic gravel and other gravels and some soils commonly used for surfaces and bases, with or without impervious surface dressings, was fairly well known. Little was known, however, about the strength and bearing capacity of sub-soils which are most important factors in aerodrome construction, since subsoil weakness has been the principal cause of such failures as have occurred.

Thus the pre-war and early wartime methods adopted for the construction of the hardstrips were based on road practice and these methods sufficed while it was only necessary to provide for D.H. 86s and 89s, and in the early days of the war for fighter and other light types of military aircraft.

By early 1943, weight of aircraft had increased up to 30 tons and some of the principal landing grounds had to cope with aircraft up to 55 tons, while further increases seemed more than likely.

It was therefore decided to make a careful investigation of the Nigerian aerodromes on or near the reinforcement route in order to assess the bearing value, and to evaluate the capacity to support aircraft of weights so much greater than was originally contemplated.

This presented a most difficult problem; existing tests were considered to be inadequate and others had to be devised which followed very closely procedure first developed in the U.S.A., but modified to meet local conditions. Although the problems were doubtless not peculiar to Nigeria, it was not known whether, or by what means, they had been solved elsewhere. It was impossible to obtain apparatus from overseas, so that it had to be devised and made locally from such material as was available and, in consequence, was a little primitive. Nevertheless, a good general indication of comparative bearing value was obtained and the causes of weakness, enabling recommendations to be made for correction.

The general results obtained from this investigation showed that at the main airports of Maiduguri, Kano and Lagos the centre line of the hardstrips possessed high bearing value and could be classified as capable of sustaining wheel-loads of 50,000 lb., although they had been used to some extent by aircraft of the 60,000 lb. wheel-load type. There was, however, a general weakness in the verges, especially when combined with the effect of turning on one wheel.

It was found* that on a really well consolidated soil a growth of grass had no detrimental effect, but that this was not the case where consolidation had been poor. This was important, as bituminous material for surfacing was difficult, if not impossible, to obtain at that time and the only economical method of protecting surfaces against erosion by wind and rain and the slipstream of aircraft was to encourage a good growth of grass.

In 1948 a further investigation on the main aerodromes was made by a Ministry of Civil Aviation party, equipped with much more elaborate and precise apparatus than had previously been available. This investigation cast doubts on the capacity of the aerodrome at Kano to carry the heavier type of aircraft likely in the future. Investigation then showed that the most economical method of improvement would be to construct an entirely new runway 9,000 ft. in length roughy parallel to, but some distance away from, the existing runway.

Interior of booking office at Enugu.

In 1949 the Air Ministry made loading tests at Ikeja which confirmed previous proposals that a new runway with high bearing capacity could best be provided by reconstructing and extending No. 2 runway to a length of 6,600 ft. It was found that scarifying and surface compaction over most of the area would achieve the desired result with the addition of a 4 in. base course of laterite with a bituminous sealing coat.

From all tests made so far, Accra aerodrome seems free from bearing value problems and capable of taking any foreseeable weight of aircraft. In its early days there was a problem of how to protect the verges of the runways from erosion as the rainfall was insufficient to support a suitable growth of grass. The solution was found in tarring the whole 200 yds. width of hardstrip and verges, and fortunately money and material were available. Its appearance, however, caused the Secretary of State for the Colonies, who on arrival was asked by a pressman for his impressions of the Gold Coast, to reply that so far as he could see it was completely covered by asphalte.

It may be asked, why all this pre-occupation with soil, and why not adopt standard practice in use in the U.K. and elsewhere? The answer is that before the war it was a question of cost. For the first six aerodromes in Nigeria only £66,000 was available. The Gold Coast were more fortunate, and about this sum was available for only two aerodromes. During the war, when costs were of less importance, it was a question of the availability of materials; cement was precious and bituminous materials obtainable in small quantities only. Plant, and even tools, were also scarce; quarrying equipment was hard to get and even more so, railway and road trucks for transport of stone. Thus, it was a question of

*Public Works Dept. Nigeria, "Aerodrome Subsoils," by R. W. TAYLOR, 1946.

making do with what was available, and soil was virtually all that could be obtained readily. After the war such progress had been made with the knowledge of soils and techniques of use that the expense of concrete and macadam was not justified. The estimated cost of the new runway at Kano is only £100,000, exclusive of the higher supervision and hire of plant.

Telecommunications

After the provision of landing grounds, the next probems were those of communications and meteorology. Up to the present time the Posts and Telegraphs Departments of the various Colonies have been responsible for communications, except in the Gambia where International Air Radio is responsible.

At the beginning, in 1936, M.F. and H.F. wireless telegraphy only was provided. There was no radio telephony or direction-finding equipment. The D.H. 86s used a "homing" device consisting of wing coils fitted to the aircraft and a small knob by which either of the coils could be connected to an aircraft receiver. In 1937, Marconi-Adcock Direction Finders were installed at Kano and Lagos. Throughout the war the R.A.F. continued to use the wireless telegraphy system set up by the Posts and Telegraphs Departments, but added their own V.H.F. and direction-finding equipment. The U.S.A.A.F. installed their own equipment but unfortunately removed it all when they left. At the end of the war a certain amount of part-worn R.A.F. equipment was left and this was maintained and modified by the Posts and Telegraphs Departments, but with difficulty.

The immediate post-war developments were concentrated on the international airports of Maiduguri, Kano, Lagos and Accra, Freetown and Bathurst, and a network of W/T. point-to-point aeronautical receivers was put up linking these stations and also those in French West Africa. The general network was agreed in 1949 at a communications meeting of the International Civil Aviation Organisation for the area.

The omni-directional beacons installed during the war were maintained and later low powered locator beacons were installed at the ends of the runways for approach purposes. Omni-directional low-power beacons were also installed at the internal aerodromes, but this took some time due to the problems in the provision of electric power and, in most instances, generating sets had to be installed. There was also a difficulty in obtaining the Radio Compasses for the aircraft, but when these were fitted there was considerable improvement in the regularity of services. In spite of delays in obtaining delivery of equipment, the aeronautical communication and navigational aids throughout the territories have steadily improved and new equipment has now replaced the obsolete sets taken over or improvised after the war.

At Kano most modern equipment has been installed, including Marconi 200 V.H.F. D/F., remotely controlled with dial reading, a high powered 2½ kw. omni-directional beacon with 200 ft. masts, new locator beacons for runway approach, and provision has been made for an I.L.S. and Eureka approach system. Teleprinter equipment is also being installed between Kano, Lagos, and Accra. Equipment similar to that at Kano is also being provided at Lagos.

Further developments which are already well advanced in the planning stage include long-range H.F. R/T. to replace the W/T. air guard in Nigeria. It is expected that within the next twelve months high-powered R/T. transmitters at Kano and Lagos will provide communication over nearly the whole of Nigeria.

The existing 100 watt beacons are being replaced by one kw. beacons at 12 of the internal aerodromes and V.H.F. R/T. is being installed at 15 internal aerodromes. It is also the intention to provide radio telephony point-to-point to operate Lagos, Kano, Accra and Port Harcourt.

Meteorological

The meteorological services in West Africa were, until October 1947, the responsibility of the Surveyors General and aviation requirements at the start, in 1936, were very simple. On the main route to the U.K. a certain amount of information was sent out from Cairo and Khartoum. In Lagos a meteorological officer went over to the aerodrome twice a week, or as required, and a synoptic chart was prepared once a day. There were 20 trained observers in Nigeria and for the most part records at outstations were kept by part-time observers, such as schoolmasters, provincial office clerks. At Accra and Freetown there were meteorological assistants. A certain amount of information was received from the French stations. Meteorological broadcasts were sent out once a day by Cables and Wireless at Accra and Freetown, and by the Post and Telegraph Department at Lagos. Communication generally was by land line.

After the fall of France in 1940, the R.A.F. posted officers to all staging posts, but the Controller of Civil Aviation continued to deal with African staff until 1943, when the R.A.F. assumed complete control. During 1946/47, while the R.A.F. were handing back the meteorological service to the Colonial Governments, a crisis was precipitated by the difficulty in recruiting civilian staff to replace R.A.F. personnel and the B.O.A.C. suspended their main line services for six weeks. The recruitment of aviation staff was made more difficult by the insistence on candidates possessing an Honours Degree.

The Meteorological Service was formed into a separate service under a Director of Meteorological Services in October 1947, at first with headquarters at Accra and after April 1950, in Lagos. Recruitment has been the main difficulty. There are now Forecasters at Kano, Lagos, Accra and Freetown. Wireless communication is now general except for about 10 stations still on land lines, but at night communication is still by land lines.

Airport Control

Aerodrome control has not presented any really serious problem. Before the war, part-time Control

African passengers at Lagos.

Officers only were necessary and during the war the R.A.F. were in control. There was a short-lived crisis at the end of the war when the R.A.F. were withdrawing and it became necessary to recruit Control Officers for the principal stations at short notice. As it was a special case and only small numbers were involved, the Colonial Office were able to streamline their recruiting procedure and reduce the time between the candidate appearing for interview and leaving for the colony. In at least one case this period was reduced to 12 days. When the local services started, the problem at minor aerodromes was solved by making the Corporation's Traffic Officers act as part-time Control Officers until such time as the Director of Civil Aviation could arrange for the training of African staff. This has now been done and the Corporation's staff relieved of their duties.

Air Service Routes

Having provided aerodromes, meteorological, wireless and control facilities, the next problem was to devise the details of the air services. This problem may conveniently be arranged under the headings of Routes, Frequencies, Types of aircraft, Staffing and training, Workshops and other ground facilities, and Traffic development.

There were plenty of aerodromes and these, even those constructed during the war, had been sited with a view to their eventual usefulness for local services at some future time. When this time came, the first problem was, therefore, what routes to operate and there was little information to serve as a guide. The R.A.F. "Bush" Service had operated for twelve months in 1945/46 on a roundabout route from Lagos to Kano, using Dakotas and carrying reasonable loads, but this was in war-time when there were severe restrictions on petrol for road vehicles, and it seemed obvious that for some years passenger traffic would consist very largely of government officials and the European employees of commercial firms. It might be thought that for routes the best way would be just to connect the larger towns with low frequency services and build up as traffic developed; but it does not work out in this way. For example, Ibadan is by far the largest town in that part of Africa, with a population of probably over 500,000, but it only produces about a dozen passengers a week.

An early decision was taken to base the network of local services on the mails and, since the Corporation was financed by public funds, this seemed the most reasonable way of ensuring the greatest benefit to the public as, although there had been much railway and road development, the average speed of movement of mails was slow. Fairly accurate information was available about the volume and direction of movement of mails and it seemed that if this basis were adopted it would not be difficult to superimpose the passenger traffic. It would also follow that the functions of the local services as feeders to the trunk line services to the U.K. would be provided for, since the large volume of external mail was almost entirely to and from the United Kingdom.

The proportion of the population which is literate is rapidly increasing and there is a steady increase in internal trade. The arguments for flying the internal mail, therefore, became more attractive the more they were considered. The Postmasters General were much in favour of the proposal and considered that it was undesirable to surcharge the internal mail.

Frequency

While it was generally accepted that the ideal frequency on any route would be once a day, it was realised that the anticipated mail and passenger loads, even with small aircraft, would not justify this even on the more important routes. From the mail point of view there are, however, minimum frequencies below which there is no advantage in carriage by air; as an example, in Nigeria between Lagos and Kano the mail trains run three times a week and transit time is 45 hours, so that unless air service frequency is at least three times a week, mail which just missed one air service would reach its destination more quickly by train than by waiting for the next air service. It was therefore decided to start with a frequency of three times a week on the more important routes and those served by the railways. Elsewhere, frequencies of once a week would be tried out initially and increased as traffic was built up. In practice it has been found that once a week is a bad frequency, twice a week is really the effective minimum, three times a week is quite satisfactory and six times is the ideal.

To provide greater frequency of service for mail purposes several of the initial services worked on a circular route, going out one way and coming back by another. This method served a useful purpose, but was not really satisfactory and the route pattern today has

settled down to the pattern familiar elsewhere, radiating out from the main centres and returning by the same route.

So much importance was attached to frequency of services as an essential to the development of air traffic that the general principle was accepted of operating with a small aircraft to start with and, as traffic increased, to work the frequency up to about six a week before changing over to larger aircraft.

These problems of routes and frequencies were local and had to be settled to meet local requirements. But before any further steps could be taken it was obvious that, for an undertaking of this nature and magnitude, it would be desirable to have an experienced associate and, most fortunately, the Chairman of B.O.A.C. agreed with this view and was willing to enter into an agreement with the West African Corporation, whereby B.O.A.C. provided advice and technical assistance, seconded experienced staff until such time as W.A.A.C. could recruit its own staff, acted as buying agents in the U.K. and arranged for one member of B.O.A.C. to serve on the W.A.A.C. Board.

Aircraft

In considering the question of suitable aircraft there seemed to be certain basic requirements, *i.e.*

(*i*) it should be all metal, as experience with wood and fabric had shown these materials to be unsuitable for West African conditions.

(*ii*) it must have two engines with a good single engine performance.

(*iii*) it should carry a radio operator as well as the pilot.

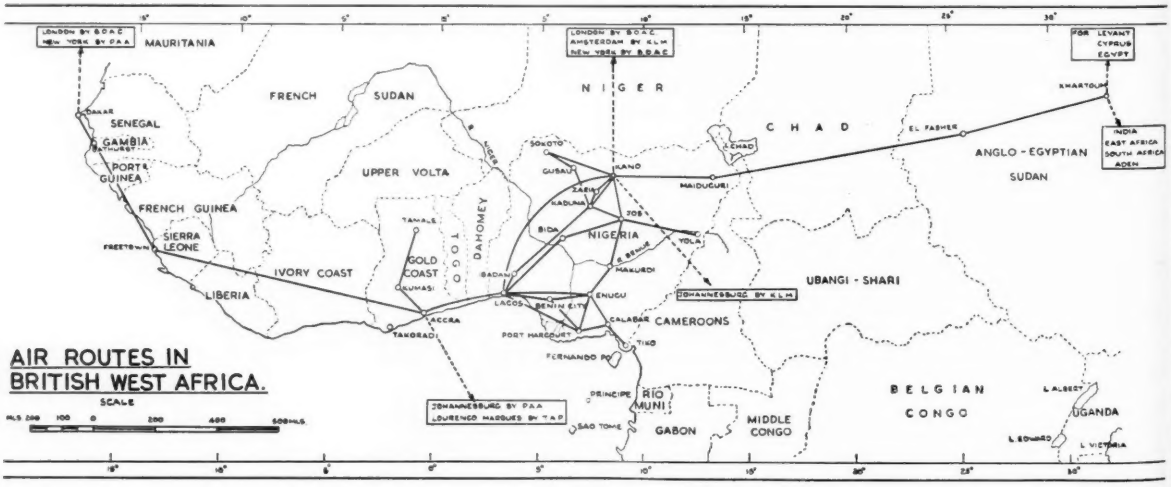
As regards size of aircraft, the only firm indication of possible load was the mail, and this did not amount to the equivalent of more than one or two passengers per service. There was no reliable indication of possible passenger loads so that after due consideration it was decided that an eight-seater aircraft would meet requirements, for a few years at any rate.

A most perplexing problem was caused by the shortness of the stage lengths on almost every route. The average length is no more than about 150 miles, often a bit less, equivalent to about an hour's flight by the type of aircraft which would be suitable. It is a well known fact that every type of aircraft has a stage length which is most economical and Mr. P. G. Masefield, in the Fourth Commonwealth Lecture in 1948, provided a wealth of information on this subject and produced charts showing very large differences in total costs per hour for different stage lengths and for different annual rates of utilisation. As examples, a de Havilland Dove on a one-hour stage with 1,000 hours utilisation a year is shown as costing £45 an hour, and for a two-hour stage with the same utilisation, £33 an hour. A Dakota, at a utilisation of 1,000 hours a year and a one-hour stage, is shown as costing £110 per hour and for a two-hour stage about £80 per hour. Such costs as are now available for operations in West Africa correspond very closely with those quoted by Mr. Masefield.

Although these problems of stage lengths and utilisation are so important from the economic point of view, it has so far not been possible in West Africa to do much about them. The centres of population are fixed and with the present volume of traffic it is not possible to overfly and still provide the mail and passenger service required by the public. At some future date it may be practical to run separate stopping and through services on some routes. As regards utilisation, it has been found that when flying is restricted to daylight hours, roughly between 8.00 a.m. and 6.30 p.m., on six days a week, it requires a great deal of skill on the part of the operations staff to get as high a utilisation as 1,200 hours a year.

The question was not, therefore, to select an aircraft which would operate at the most profit but rather that on which the least loss would be incurred and there was thus really only one possible choice, the de Havilland Dove; 10 of these aircraft were purchased.

Nevertheless, at quite an early stage consideration was given to ordering a larger type of aircraft to be



available about 1948 or 1949. Also, at this early stage, it had been found that there was among the travelling public in West Africa a very strong four-engine complex, much stronger in fact than appears to have been experienced anywhere else in the world. Here, also, there was a difficulty, since most four-engined aircraft were far too large for the possible increase in traffic in so short a period. An increase from eight-seater to eighteen or twenty-seater was considered the most that traffic would stand and give a reasonable load factor, of say 65 per cent. The Miles Marathon 18-seater appeared to be the most suitable and had the added attraction of having the same Gipsy engines as the Doves, making the problem of spares and workshop equipment much easier. Unfortunately, these aircraft were not delivered until late 1952 and early 1953, so that it is too early as yet to comment on results, but it would seem that they have appealed to the potential passenger with a four-engine complex, since in the first two months, and in spite of the considerable increase in capacity over the Doves, they showed a load factor of 50 per cent.

When in 1950 the W.A.A.C. was required to operate the Lagos—Dakar and Lagos—Khartoum routes, which were quite unsuitable for Doves because of the long stages, the choice of aircraft was influenced by two main considerations.

(*i*) In 1949 the Corporation had been required to operate two Bristol 170 Freighters under a management agreement and so had recruited engineers and held a stock of spares.

(*ii*) The M.C.A. was prepared to hire two Bristol 170 Wayfarers on favourable terms, thus avoiding any capital expenditure.

Although the Bristols are rather slow for these long routes and their carrying capacity is such that the traffic offering does not justify the frequency desirable, it was considered that the factors mentioned in (*i*) and (*ii*) outweighed these considerations.

Staffing

One of the most difficult problems has been staffing. It was hoped that, as a result of the intense military aviation activity during the war years, there would be produced a considerable number of Africans trained in maintenance work and general ground duties; but this was not so, as both the R.A.F. and B.O.A.C. were much too busy to spare time for training. This meant that after the war, when the W.A.A.C. organisation had to be set up, a much larger proportion of imported European staff had to be employed than would otherwise have been necessary, and the subsequent expansion of the Corporation's activities has been so rapid that, although training schemes have been started, the numbers produced so far have been, and will be for some years, insufficient to meet the demand. Fortunately it was possible to arrange for B.O.A.C. to second from their own staff engineers and traffic officers to enable operations to begin.

In the meantime steps have been taken to recruit direct to W.A.A.C. and much progress has been made, but it is a slow and tedious process building up a staff under West African conditions. There are no local candidates as in East and Central Africa, and recruitment has to be done in the United Kingdom. Tours of duty are short, 15 to 18 months, and the leave period from 3 to 4 months necessitates a large reserve on the establishment for leave. The leave and sickness reserve required amounts to 25 per cent. In spite of difficulties, progress has been made and out of a total strength of 221 only 40 are now seconded from the B.O.A.C. The turnover of staff is always high in West Africa and means that many more than 221 have had to be recruited. It is calculated that under normal conditions the numbers required to be recruited each year as replacements from all causes will amount to about 12 per cent. of the establishment.

A major preoccupation has been the building of quarters for staff, since it is not possible to rent suitable quarters. A building programme had to be put in hand right at the start and has continued to the present time, involving an expenditure of £800,000, which is a heavy capital charge for a small undertaking. The building programme has also had to include offices at some stations, although at Lagos the Headquarters offices and workshops on the aerodrome were built by the Nigerian Government and are let to the Corporation at a rent based on the actual cost. When it is realised that all European staff have to be provided with free fully-furnished quarters costing between £4,000 and £5,000, passages from and to the United Kingdom every 15 months for themselves, their wives and often children, a pension fund contribution, and that the minimum salary is £830 per annum, the seriousness of the problem of economic utilisation of supervisory staff becomes understandable.

The African staff problem was rather different in that during the war the B.O.A.C. employed very large numbers of unskilled labour of all sorts, and also large numbers of untrained, or only partly trained, clerks far in excess of the modest requirements of W.A.A.C.; the problem was one of sorting them out and reducing the number to that required and starting training schemes. This was a most difficult operation and was very skilfully carried out by the General Manager with a minimum of disturbance. The local establishment now numbers 876 of all grades.

The training scheme for engineering staff works in conjunction with the Trade Training School of the Education Department but, owing to the length of time required and the almost total absence of trained men at the start, progress has been slow. More rapid progress has been made with Traffic Staff and Africans are now in charge at all but the five major stations.

During the war a very few Africans were trained by the R.A.F. as pilots, but none of them continued in that occupation afterwards and the experience gained in this direction was lost. However, a scheme is now being considered by the West African Governments for training pilots, under which initial basic training will be provided in the U.K. and subsequent flying experience given by the Corporation in West Africa.

Workshops

The initial problems in connection with the engineering base and workshops was, where to establish them. At Accra there was ample hangar, workshop and store accommodation, and two 150 ft. span hangars, while at Lagos there was only one 100 ft. Bellman hangar and a few small buildings not at all conveniently sited; there were also two Bellman hangars at the disused landing ground at Apapa, which could be moved to Ikeja. On the other hand, Lagos was bound to be the centre of gravity of the traffic.

The temptation to make use of superior existing accommodation was very strong but it was obvious that, even if the base were established at Accra, a very extensive subsidiary establishment would be necessary in Lagos with consequent dispersion of supervisory staff and stores. The decision was therefore in favour of Lagos. The existing buildings provided very cramped temporary accommodation until new buildings could be designed and erected. It was difficult to foresee future developments, but it was considered prudent to provide workshops, stores, etc. to deal with twice the number of aircraft and engines then contemplated (1947), *i.e.* 7 Doves and 3 Marathons. The requirements were thus estimated at engine overhaul shop 12,285 ft.^{2}, propeller overhaul shop 1,060 ft.^{2}, component overhauls 3,200 ft.^{2}, stores 4,800 ft.^{2}. The engine and propeller areas have proved adequate to meet the increase in the number of engines dealt with, and the component overhaul area has sufficed because large numbers are sent to the U.K. for overhaul. But the stores area was grossly underestimated because it was originally thought that a nine months' stock of spares would be sufficient, whereas in practice it has been found desirable to increase this to 18 months to two years. Extensions are now in hand to the stores and ancillary shops.

The engine overhaul workshop is of simple design, 105 ft. × 117 ft. with stores at one end and ancillary shops at the other, and the remaining two sides open except for expanded metal screens, so as to obtain as much ventilation as possible. The building is on a site sheltered from strong winds and very little trouble has been experienced from dust and rain, certainly not nearly enough to offset the better ventilation provided by open sides. Air conditioning has been provided in some of the small specialist shops, but a great deal more knowledge and experience is required on this subject before it becomes really satisfactory.

Another siting problem arose over the Headquarters Administrative offices which, at first, were housed in a building in Lagos formerly rented by the B.O.A.C. After long consideration it was eventually decided that the administrative headquarters would be better sited at the aerodrome and adjacent to the workshops and stores, and that all that was really required in Lagos town was a booking office.

Passenger Accommodation

While many operators have been faced with the problem of building night-stop accommodation for passengers, the problem at many stations in West Africa also included making similar provision for stop-over and return-passengers. It was realised at an early stage that for some years a large proportion of the passengers on the internal services would be Government officers and the agents of commercial firms travelling on duty, who only wished to spend a few nights at each place. Except at Kano, Lagos and Accra there were no hotels and in Nigeria the rest-houses did not provide catering services and were generally unfurnished. Travellers by road had perforce to travel self-contained and take with them servants, beds, baths, tables, chairs, cooking utensils, crockery, glass, provisions, etc. For journeys of short duration this could be done in vehicles of the kitcar or station wagon type, but frequently a 30 cwt. or 2-ton lorry was necessary. It was, therefore, apparent that, if the internal air services were to be of maximum

Second class passengers embarking in a Bristol 170 at Lagos.

use to these travellers, fully furnished rest-houses providing catering accommodation would be necessary.

A scheme was prepared which provided for building a standard type of rest-house, comprising a dining room and lounge block and the bedrooms, each with a bathroom in blocks of two separate from the main block, so that the number of bedrooms could be added to without difficulty as the demand increased. The numbers required at each station could only be guessed at, and there was considerable doubt among older members of the community as to whether such an innovation would ever be practicable. A start was made and rest-houses of this type were provided by the Nigerian Government at each station where there was an aerodrome, by the time the internal air services started.

The scheme has proved most successful and has now been extended to other places on the motor-roads where there are as yet no aerodromes, while at the main stations considerable expansion has been necessary to cope with travellers by road and train to the extent that in some places the air travellers are well in the minority and it has almost been forgotten that the air services were originally the reason for building the resthouses. Although they were built and are run by the Government, they were very much a problem for the D.C.A., who was also chairman of the Airways Corporation.

Traffic

It has already been mentioned that while some estimate could be made of the probable post-war development of the external air traffic to the U.K., there was little information on which to form any estimate of probable internal traffic, and it was necessary to proceed with caution. There was also the possibility that the numbers able and willing to pay the ordinary air fare of 8d. to 10d. per mile would be limited, in view of the comparatively small numbers of Europeans and well-to-do Africans, and this possibility has always had to be borne in mind. While the numbers of passengers paying ordinary fares is still increasing, it has been felt that saturation point may not be far away, although it would be most rash to attempt to prophesy.

An interesting development in 1949 was due to the Corporation being required to operate two Bristol 170 Freighters under a management agreement, which required the Corporation to use its best endeavours to earn revenue during the time the aircraft were not required for other duties. By installing a very austere type of seat it was found possible to accommodate 56 passengers on short stages and this provided an opportunity for experimenting with second class traffic on internal routes. After much discussion it was decided to fix the fares initially at 4d. per passenger mile and to start on a route service between Accra and Kumasi, as very large numbers of Africans travel between these two places by railway and road. It might be thought that it would have been better to start on a route where there was not so much competition from other forms of transport, but it was felt that as an experiment it was desirable to find out whether air travel at a cheap rate could compete. This pilot service had rather a chequered career and was subject to considerable irregularity owing to other demands on the aircraft. Nevertheless, it demonstrated that air travel at cheap rates was liked by the general public and an additional Bristol 170 was bought so that the services could be extended to Lagos, Port Harcourt and Kano.

The way in which the second class traffic is increasing and the fact that there is a distinct tendency for passengers who would normally be expected to pay the ordinary fares to travel by the cheaper services, indicates that, as the cheaper rate services are developed, the rate of increase in traffic on the ordinary services will diminish and the ultimate solution may well be a single class service at a rate possibly slightly higher than the present second class, say 5d. or 6d. per mile instead of 4½d., although here again it is dangerous to forecast on present information. The following figures for passengers carried on 1st and 2nd class internal services, and on the external services are of interest:

	1948/49	1949/50	1950/51	1951/52	1952/53
Internal Services 1st class	13,813	14,538	24,872	30,346	33,234
Internal Services 2nd class		561	6,268	12,423	23,955
Total Internal Services	13,813	15,099	31,140	42,769	57,189
External Services to U.K.	7,928	11,299	15,711	17,269	

It will be seen that the internal second class traffic has increased much more rapidly than either the first class internal, or the external, traffic both of which show similar proportional increases. More recently there has been an even more pronounced increase and second class passengers now number some 2,600 per month and first class internal, 300 a month. The position thus creates a difficult problem in re-equipment as it may not be just a question of having the same type of aircraft for both kinds of service, with different seating capacities, but of two different types of aircraft because of the necessity for maintaining frequencies on the first class service.

This question of re-equipment is probably the biggest problem facing the small operators today because of the ever-increasing cost of aircraft. Sir Leonard Isitt discussed this problem in his British Commonwealth Lecture in 1951, and the difficulties, if anything, have become even greater in the meantime.

Under present conditions re-equipment will be necessary every seven to 10 years, at least, and with the vastly increased costs of modern types of aircraft, the cost cannot be met from the ordinary depreciation and sinking funds and large additional capital is necessary. It may be contended that the higher speeds of modern aircraft will more than compensate for the additional costs, but it will not always be that the small operator with short routes can obtain the full utilisation possible with these higher speeds. An aircraft with a speed of, say 300 miles per hour, does not necessarily do twice as much work as an aircraft with a speed of 150 miles per hour, but the capital cost is probably three times. The travelling public is getting used to ever higher speeds on the main trunk lines and will expect at least a proportionate increase in the feeder services, so that the small

operator may be forced to re-equip with faster and more extensive aircraft, if he is to maintain his traffic; that is to say, if he can raise the necessary capital and face increased overall cost until the utilisation can be built up to match the higher speed.

It is hoped that this description of the various stages necessary to develop air transport in British West Africa has been of interest as showing the diversity of problems which have had to be overcome.

ACKNOWLEDGMENT

I should like to express my thanks to Wing Commander E. H. Coleman, A.F.C., Director of Civil Aviation West Africa, and to Mr. Stonehouse, Colonial Meteorological Service, for their assistance in refreshing my memory on many matters, particularly in connection with telecommunications and meteorological services, and to Mr. Granville of B.O.A.C. for the estimated traffic figures.

THE PRESIDENT, in expressing his appreciation of the paper, said it appeared that the West African Airways Corporation was very much up to date and was doing a strikingly successful job. He had to confess that his knowledge of the places mentioned by Sir Hubert arose largely from his earlier activities as a stamp collector but, although that was the extent of his acquaintance with the country which Sir Hubert had obviously served so well, he was none the less sincere in expressing the pleasure which he had felt at listening to a plain tale of hard work, the success of which must surely be gratifying both to West Africa and to Sir Hubert.

MR. P. G. MASEFIELD (Vice-President of the Society, *Fellow*), proposing a vote of thanks to the lecturer, said it was appropriate that they should be holding the meeting for the Ninth British Commonwealth and Empire Lecture at a time when the Commonwealth Air Transport Council was meeting in London.

It was interesting to remember that West Africa had not only produced West African Airways but also the first Minister of Civil Aviation in this country, Lord Swinton, who had come hot-foot from West Africa to London to take up his duties.

While Sir Hubert had illustrated some of the problems encountered by a small airline operating under very difficult conditions in places known chiefly by stamps and old tales of slave-trading, such as the Gold Coast and the Ivory Coast, there was one problem which had not been mentioned in the lecture, and that was that having checked in 40 people in the Bristol Wayfarer one got out to the end of the runway and on a count of heads found that there were substantially more people inside the aircraft, the reason being that the women passengers had each produced three or four piccaninnies from under the folds of their voluminous garments! That was one difficulty which was not encountered on the Paris run!

Following the Lecture a Dinner was given by the President and Council of the Society at 4 Hamilton Place, W.1, at which the following were present:—

Captain L. R. Ambrose, London Representative of Qantas Empire Airways.

Dr. A. M. Ballantyne, T.D., A.F.R.Ae.S., Secretary of the Royal Aeronautical Society; Professor A. D. Baxter, M.Eng., M.I.Mech.E., F.R.Ae.S., Professor of Aircraft Propulsion, College of Aeronautics, Member of Council; Brigadier C. S. Booth, Canadian Representative on the Council of the International Civil Aviation Organisation; Mr. E. C. Bowyer, C.B.E., Director of The Society of British Aircraft Constructors; Sir John S. Buchanan, C.B.E., A.M.I.Mech.E., F.R.Ae.S., Past President of the Royal Aeronautical Society and Member of Council; Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Director of Construction and Research Facilities of the Ministry of Supply, Past President of the Royal Aeronautical Society and Member of Council.

Mr. S. Camm, C.B.E., F.R.Ae.S., Director and Chief Designer of Hawker Aircraft Ltd., Vice-President of the Royal Aeronautical Society; Dr. R. Cheetham, M.B., Ch.B., M.A., Ph.D., A.F.R.Ae.S., Vice-President of the Southern Africa Division of the Royal Aeronautical Society.

Mr. O. N. Dang, Indian Representative on the Council of the International Civil Aviation Organisation; Mr. G. H. Dowty, F.R.Ae.S., F.I.A.S., Chairman and Managing Director of Dowty Equipment Ltd., Past President of the Royal Aeronautical Society and Member of Council.

Mr. G. R. Edwards, C.B.E., B.Sc., F.R.Ae.S., Director, General Manager and Chief Engineer Vickers-Armstrongs Ltd., Vice-President of the Royal Aeronautical Society.

Sir William S. Farren, C.B., M.B.E., M.A., F.R.S., F.R.Ae.S., Technical Director of A. V. Roe & Co. Ltd., President of the Royal Aeronautical Society.

Mr. A. A. Hall, M.A., F.R.S., F.R.Ae.S., Director of the Royal Aircraft Establishment, Member of Council; Mr. N. J. Hancock, A.F.R.Ae.S., Ministry of Supply (Aeronautical Inspection Department), Member of Council; Sir William Hildred, C.B., O.B.E., M.A., Director-General, International Air Transport Association.

Mr. E. T. Jones, C.B.E., M.Eng., F.R.Ae.S., Principal Director of Scientific Research, Ministry of Supply, Member of Council; Dr. O. H. Wansborough-Jones, C.B., O.B.E., M.A., Chief Scientist, Ministry of Supply.

Lord Douglas of Kirtleside, G.C.B., M.C., D.F.C., Chairman of British European Airways Corporation.

Captain A. G. Lamplugh, C.B.E., F.R.Ae.S., F.R.G.S., Underwriter and Principal Surveyor, The British Aviation Insurance Co. Ltd.

Mr. P. G. Masefield, M.A., F.R.Ae.S., F.I.A.S., Chief Executive, British European Airways Corporation, Vice-President of the Royal Aeronautical Society.

Mr. J. R. Naisby, Representative of South African Airways.

Sir Frederick Handley Page, C.B.E., Hon.F.R.Ae.S., Hon.F.I.A.S., Chairman and Managing Director, Handley Page Ltd., Past President of the Royal Aeronautical Society; Mr. J. C. Patteson, C.M.G., Canadian Pacific Airways; Colonel R. L. Preston, C.B.E., A.F.R.Ae.S., Secretary-General of the Royal Aero Club; Captain J. Laurence Pritchard, C.B.E., Hon.F.R.Ae.S., Hon.F.I.A.S., Past Secretary of the Royal Aeronautical Society 1925-1951, Member of Council.

Mr. N. E. Rowe, C.B.E., B.Sc., D.I.C., F.R.Ae.S., Technical Director of Blackburn & General Aircraft Co. Ltd., Member of Council; Mr. J. G. Roxburgh, Grad.R.Ae.S., Handley Page Ltd., Member of Council.

Mr. T. Shelly, London Representative of Aer Lingus; Mr. B. S. Shenstone, M.A.Sc., F.R.Ae.S., Chief Engineer of British European Airways Corporation, Member of Council.

Mr. W. Tye, O.B.E., B.Sc., F.R.Ae.S., Chief Technical Officer of the Air Registration Board, Member of Council; Sir Frederick Tymms, K.C.I.E., M.C., F.R.Ae.S., United Kingdom Representative on the Council of the International Civil Aviation Organisation.

Mr. C. F. Uwins, O.B.E., A.F.C., F.R.Ae.S., Managing Director, Aircraft Division of The Bristol Aeroplane Co. Ltd., Honorary Treasurer of the Royal Aeronautical Society and Member of Council.

Sir Hubert Walker, C.B.E., M.I.C.E., Reader of the Ninth British Commonwealth and Empire Lecture 1953, Chairman of the West African Airways Corporation; Dr. Edward Warner, M.S., M.A., D.Sc., Hon.F.I.A.S., Hon.F.R.Ae.S., President of the Council of the International Civil Aviation Organisation; Air Marshal R. Williams, C.B., C.B.E., D.S.O., Director General of Civil Aviation, Australia; Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor to the Royal Aeronautical Society.

A Modern Wind Tunnel Balance

by

L. E. LEAVY, A.F.R.Ae.S. and C. G. SAUNDERS
(Blackburn and General Aircraft Ltd.)

1. Introduction

Because of the limited nature of its application the wind tunnel balance has never been the subject of steady development along well defined lines such as are discernible in the development of most other mechanisms of comparable size and complexity.

The diversity of types and forms of balance which have been constructed in the past, reflect the wide range of tunnel sizes, financial resources, and personal preferences which are characteristic of some laboratory equipment.

The design and construction of a balance suitable for use in a medium-to-large industrial wind tunnel is a relatively costly undertaking, and the problem of providing such equipment is made more difficult by the paucity of published information, of a sufficiently detailed nature to be of assistance in making a decision on either a suitable specification for this class of machine, or the practical means by which a specification can best be met.

As part of the modernisation of the Blackburn and General Aircraft Aerodynamics Laboratory at Brough, a new six-component balance was installed, some few years ago, in a 7 ft. × 5 ft. wind tunnel having a maximum speed of 300 ft./sec. A detailed description of this balance is given.

In planning for the supply of this apparatus, it was realised that no wide field of experience in the design and operation of this type of equipment exists outside an aerodynamics laboratory, and as routine maintenance in any case devolves on the wind tunnel staff, it was decided to design and construct the balance in the aerodynamics laboratory, so that those using the equipment would have an intimate knowledge of the mechanism from its inception.

Considerations of delivery time, and the difficulty of getting others to interpret the requirements fully, were other factors influencing this decision, and after four years of intensive use, the new balance has proved to be very satisfactory, and has wholly justified this course of action.

2. Balance Specification

2.1. GENERAL REQUIREMENTS

Past experience had indicated that a satisfactory balance for use on a tunnel of this type, should have the following characteristics:—

(*a*) The ability to measure the three forces and three moments on a model simultaneously and independently over a wide range of angles of incidence and yaw.

(*b*) The accuracy of any one of the six components should not be impaired by any combination of loads in the other five, and should not be less than 0·05 per cent. of the maximum permissible load in each system, or 0·5 per cent. of the applied load, whichever is the greater.

(*c*) Robustness and relatively simple design, calling for minimum maintenance.

(*d*) Rapidity of operation.

(*e*) Ease of model installation.

It is perhaps appropriate to comment on these requirements since they are to some extent controversial.

With regard to (*a*), a feature of certain balance designs has been that some components are measured indirectly, as a function of the sum or difference of the readings of two or more components. This results not only in an inevitable loss of accuracy, but also precludes the rapid checking and comparison of measurements during the course of the test.

The limits of accuracy set out in (*b*) may, at first sight, seem coarser than desired, but experience has shown that to attempt a higher standard of accuracy in what is, after all, a general purpose instrument is both unnecessary and undesirable. An effort to design a balance capable of measuring to closer limits of accuracy, is pointless, unless similar standards are to be expected from the measurement and quality of the tunnel air flow and the accuracy of model construction. It is sometimes overlooked that the precision of a result in practice is not greater than that of the slide rule and commercial graph paper invariably used in the reduction process.

With regard to (*c*), the design should be simple enough to enable the balance to be maintained by personnel with a general engineering training, without the necessity to call in specialists, at the same time, over simplification in the design is to be avoided, since it is likely to produce a machine which requires an excessive time to carry out a given volume of work.

Unlike pure research work, the time factor is all-important in an industrial tunnel engaged on aircraft design work, and the value of the information which it provides is a maximum, only if it is given to the design staff within a reasonable time. This fact has been recognised in requirements (*d*) and (*e*).

It has been found that the time scale to cover a full programme of tests covering all the normal performance, control and stability parameters, both power on and off, can now be measured in weeks as compared to months

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with less elaborate equipment. It is considered that the resultant design is a satisfactory compromise.

2.2. BALANCE LOAD RANGE

The normal load ranges considered necessary for a balance suitable for this tunnel are given in Table I. It was thought desirable for special tests, particularly on high-speed designs of low aspect ratio and consequently relatively large chord, that these load ranges should be capable of being readily doubled, and provision for this was made in the design.

The corresponding coefficient ranges on two models, one of modest size tested at the normal tunnel speed of 250 ft./sec., and the other of relatively large size, tested at the maximum speed of the tunnel, on which the doubling weight would be employed, are given in Table II.

Several features of the balance are not novel, but an attempt to combine the better features of some earlier designs has been made, without sacrificing the desirable qualities enumerated in Section 2.1, while it is thought that certain details have not previously been incorporated in balance design.

TABLE I

NORMAL BALANCE LOAD RANGE

Lift	[− 100 lb. + 900 lb.]	Pitching moment	[± 100 lb. ft.]
Drag	[− 50 lb. + 150 lb.]	Rolling moment	[± 350 lb. ft.]
Drift	[± 125 lb.]	Yawing moment	[± 125 lb. ft.]

3. Balance Geometry

3.1. GENERAL LAYOUT

The balance, which is of the virtual centre type, measures the forces and moments about a system of gravity axes having the virtual centre as origin. This enables the measurements on the model to be taken about a representative full scale c.g. position, thus saving subsequent computing work, and enabling broad conclusions to be made directly from the tunnel results, and has considerable value during *ad hoc* testing. Simple miniature fittings in which friction is of no importance can be used to support the model, and this

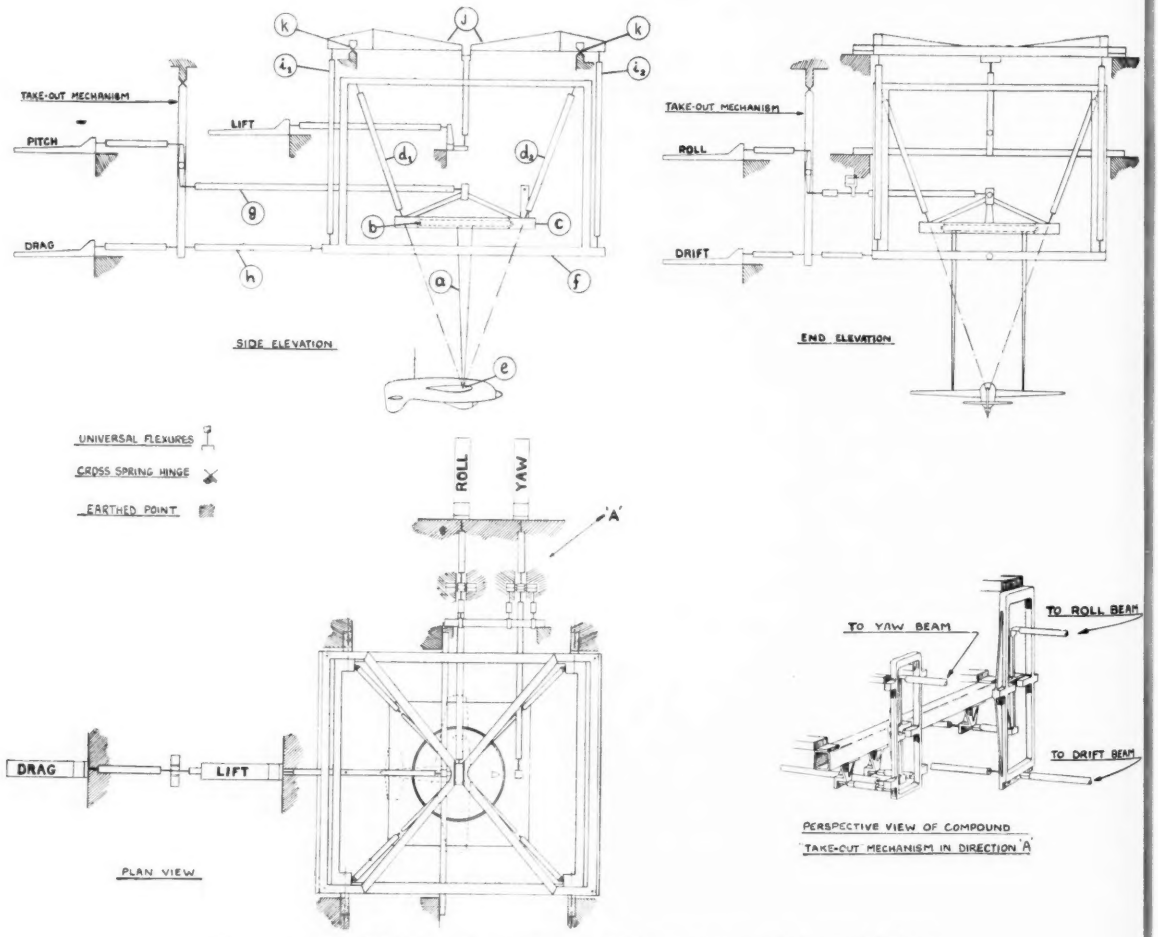

FIGURE 1. Simplified general arrangement of six-component wind tunnel balance.

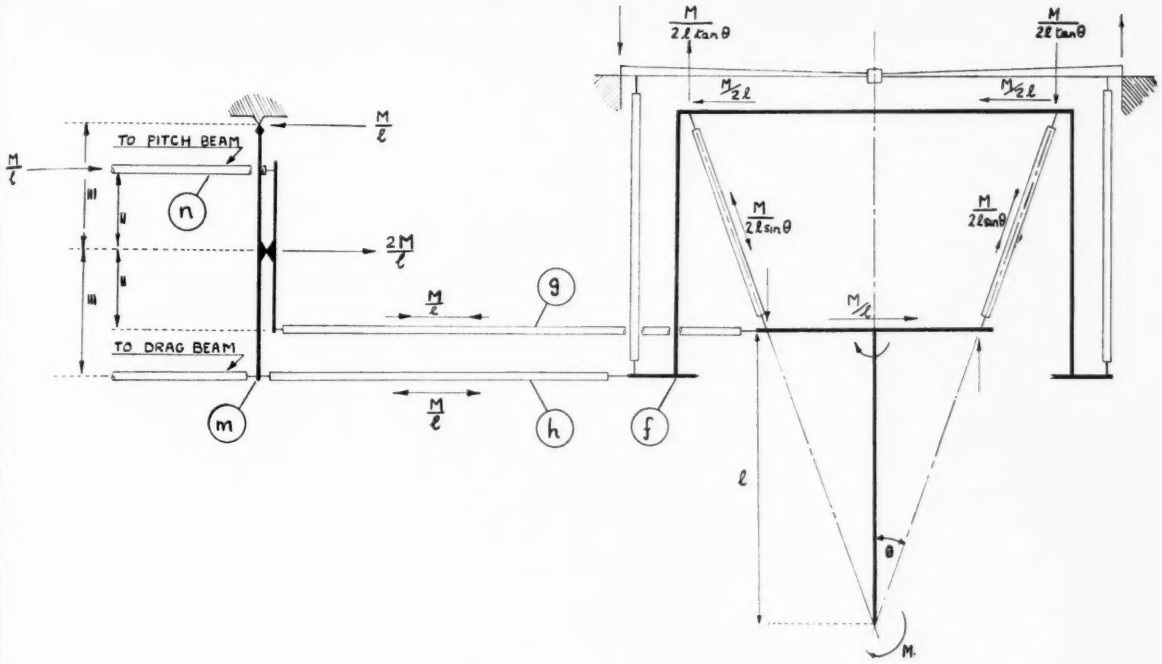

FIGURE 2. Separation of moments from forces system by means of "take-out" mechanism.

is a valuable feature, due to the current trend towards very low thickness/chord ratios in modern aircraft wings. The ability to feed in electrical wires, pressure tubes, etc., through the model arms to the model, without introducing frictional effects, is also of great benefit.

The model is supported in the air stream at the extremity of two rigid arms (*a* in Fig. 1), which terminate in ball and socket joints on a horizontal line passing through the virtual centre, as indicated by the broken lines in the diagram. The arms are carried from a large turntable, *b*, permitting rotation of the model in yaw through $\pm 175°$. A small electric winch is carried on the turntable; together with a steel cable it forms the third model support, and is used to change the angle of incidence of the model.

The turntable is carried in the moment frame, *c*, which is itself supported by the four inclined links d_1, d_2 --- from the force frame *f*. The centre lines of these links lie along the edges of a truncated pyramid, with apex at the virtual centre, and are provided with universal flexures at either extremity. The properties of such a system are, that a force applied at the virtual centre *e*, produces only direct axial loads in the links d_1, d_2 --- and consequently, the force is transmitted through the force frame *f*, the pyramid system acting as though it were a rigid structure. If, however, a moment or couple is applied about *e*, a collapsing moment is produced in the flexures situated in d_1, d_2 --- and this collapsing moment is resisted by members such as *g* in Fig. 1, which are in turn connected to the appropriate moment weighbeams.

Parallel motion in the horizontal plane is imparted to the force frame *f* by virtue of four long vertical links i_1, i_2 --- which are suspended from the lift totalisator beams *j*. The vertical links, which are provided with universal flexures at either end, give freedom to the force frame in the drag and drift directions, and the frame is constrained by links such as *h* in Fig. 1, coupled to the force weighbeams. The lift totalisator beams are pivoted at *kk* to the earth frame, a portion of the lift load being transmitted *via* a bell crank lever to the lift weighbeam.

A diagrammatic sectional view through the balance centre line is also shown in Fig. 1, in which it will be seen that the drift and rolling moment systems are similar to the drag and pitching moment systems, but lie in a plane at right angles, while the yawing moment system lies in a parallel plane displaced some 20 in. from the turntable centre line.

TABLE II

TYPICAL BALANCE COEFFICIENT RANGE

Normal conditions		*Large model. Doubling weight used*	
8 in. × 48 in. wing	$V = 250$ ft./sec.	60° Delta $b = 48$ in.	$V = 300$ ft./sec.
$C_L \begin{bmatrix} -0.5 \\ +4.5 \end{bmatrix}$	$C_m \pm 0.75$	$C_L \begin{bmatrix} -0.25 \\ +2.40 \end{bmatrix}$	$C_m \pm 0.15$
$C_D \begin{bmatrix} -0.25 \\ +0.75 \end{bmatrix}$	$C_l \pm 0.45$	$C_D \begin{bmatrix} -0.13 \\ +0.40 \end{bmatrix}$	$C_l \pm 0.23$
$C_Y \begin{bmatrix} -0.6 \end{bmatrix}$	$C_n \pm 0.16$	$C_Y \begin{bmatrix} \pm 0.33 \end{bmatrix}$	$C_n \pm 0.08$

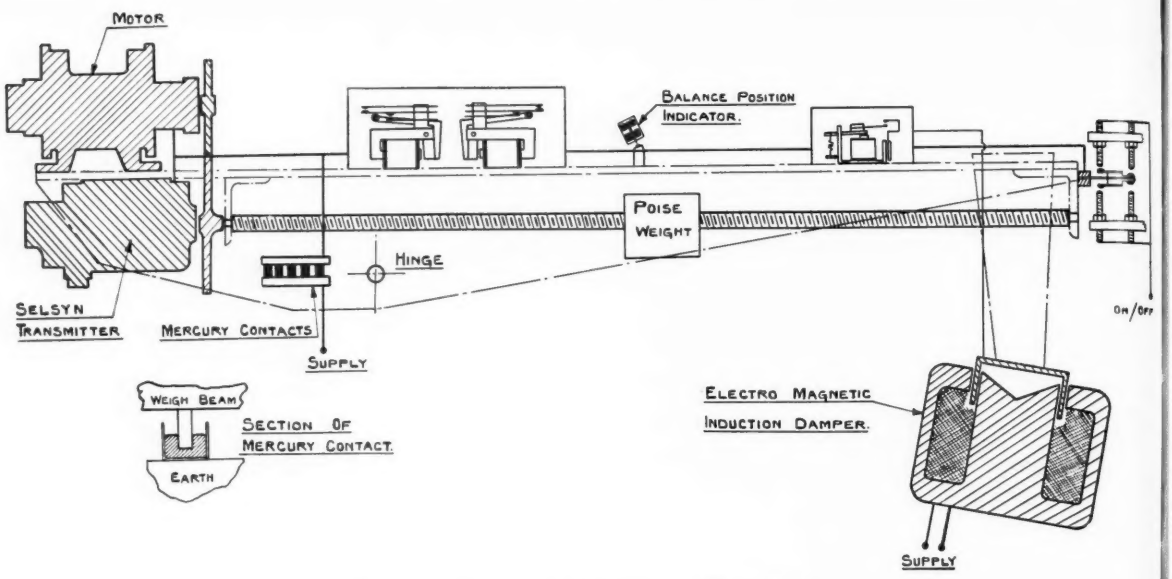

FIGURE 3. Arrangement of automatic weighbeam unit.

3.2. THE "TAKE-OUT" MECHANISM

It will be seen that each weighbeam fulcrum is attached to the "earth" frame supporting the balance mechanism. To avoid interaction between the various systems, a "take-out" mechanism is necessary.

The manner in which the "take-out" mechanism functions may be seen by reference to Fig. 2. Consider a pitching moment M on the model, which is reacted by a force M/l in the pitch draw link g. An equal and opposite force is produced in the force frame f, and will be transmitted along the link h. Without the use of a "take-out" mechanism this would produce a deflection of the drag weighbeam until equilibrium conditions were restored, and this effect would nullify the whole conception of direct and independent measurement of each component.

The "take-out" mechanism, shown diagrammatically in Fig. 2, is inserted between the pitching moment and drag draw links and consists of a long swing link m "earthed" at its upper extremity, the lower end being interconnected in the drag draw tube which is divided for this purpose. At the midpoint of m a vertical rocking lever is pivoted, one end of which is coupled to the pitch draw link g, the other to the pitch weighbeam.

The operation of the "take-out" mechanism is such that the force M/l in the link g induced by a pitching moment M on the model, is reacted by the pitching moment weighbeam through the upper pitch draw link n, with the result that a reaction equal to $2M/l$ in magnitude is produced at the rocking lever fulcrum. The moment about the swinging link fulcrum is reacted by a force M/l of opposite sign in the drag draw link h. Consequently, no force is transmitted past the "take-out" mechanism to the drag weighbeam system, when a couple acts on the model.

This device is also used between the rolling moment and drift systems and, in a modified form, to eliminate yawing moment reactions from both the drift and rolling moment systems (as shown in the perspective view given in Fig. 1).

3.3. FLEXURE PIVOTS

The balance operates on the "null" method as is usual in this type of equipment so that in the balanced-out condition the geometry is unimpaired and the model undisturbed. This principle has an important bearing on the design, since it permits all joints and hinges to be of the flexure pivot type. These flexures are essentially free from the hysteretic effects caused by friction and lost motion which occur in other types of pivots and bearings, and they have been used in test equipment for the last fifty years. In the present application, where single axis rotation is required, multiple 30 S.W.G. spring steel strips are used with a free length of 0·062 in. while, for the universal flexures, a 0·6 per cent. carbon steel spindle, centre ground to a diameter of $\frac{3}{16}$ in. over a length of $2\frac{1}{2}$ in., is used. The universal flexures carry left and right hand threads and form a useful means of levelling and centralising the balance frames during the setting-up process. It was found essential that these flexures should be concentric if the desired degree of accuracy was to be obtained, and warpage after heat treatment gave trouble initially.

3.4. STIFFNESS REQUIREMENTS

In a balance using this type of flexure it is essential that elastic deflections under load are reduced to a minimum and this requirement is also inherent in the use of the virtual centre principle, which is sensitive to small misalignments.

For the full designed loads the deflections have been kept down to the values given in Table III, measured

in each case at the virtual centre with the weighbeams centralised and locked, the load being applied at the model supports.

TABLE III

Lift	0·033 in.	Pitch	0·005 in.
Drag	0·097 in.	Roll	0·017 in.
Drift	0·087 in.	Yaw	0·005 in.

It should be stressed that these are the deflections measured from end to end of each system with the other five unloaded. Only a portion of the deflections can be attributed directly to deformation of the virtual centre mechanism itself. This requires that great attention be paid to the stiffness of all parts.

4. Automatic Weighbeam Unit

4.1. GENERAL DESCRIPTION

The weighbeam units used in all six systems are essentially similar (Fig. 3). The principle employed is that of a poise weight traversed along the length of a steelyard by means of an accurately cut lead screw, which is driven through a train of gears by an electric motor. The motor is energised through contacts attached to the beam, so that when the beam is displaced from the equilibrium position, the poise weight is driven in the appropriate direction for balance. A "Selsyn" transmitter driven directly from the lead screw shaft is wired to a receiver on the balance console, which in turn, is geared to a "Veeder" type four-figure counter, in which the last figure represents 1/20 of a turn of the lead screw. Assuming no backlash in the system, the position of the poise weight in the beam is determined to within 0·003 in. by the last figure on the counter.

4.2. WEIGHBEAM DEVELOPMENT

The development of a satisfactory weighbeam was done on the experimental beam shown in Fig. 4, in which the main features may be seen to advantage.

It was found that, in order to maintain the required sensitivity under all conditions and, at the same time, to maintain sufficient stability to prevent "hunting," great care was necessary in the detail design of the beams, and the following features were found to be essential to this particular application.

To reduce end float and the effects of wear to a minimum, the lead screw was made from high grade steel, having a ground thread of "Acme" profile with 15 threads per inch. A split phosphor bronze half nut, loaded both axially and radially by stiff springs is enclosed in the poise weight, and by these means it was found possible to reduce end float on the weight to 0·001 in. and to compensate for wear at the same time. Bending of the lead screw is avoided by supporting the poise weight on two ground bars aligned parallel with the lead screw axis.

A $\frac{1}{8}$ h.p. 24-volt shunt-wound reversible electric motor is mounted above the beams, driving the lead screw through 10 : 1 reduction gearing. The special motor, which was supplied by Newton Brothers, is provided with dynamic braking so as to minimise overrun when the motor circuit is broken, and it is possible to bring the lead screw to rest within 0·07 of a turn when the motor is running at its normal speed of 2,000 r.p.m. The field winding is continuously energised even with the motor stopped and must be designed to take the full current under these conditions. Two sets of contacts are used to give two-speed running of the motor so that, with the beam heavily out of balance the motor runs at full speed while, as the balanced position is approached, motor speed is reduced to about 1/10 of normal speed, by means of a resistance switched into the armature circuit. This is in some respects similar to the German A.1 steelyard.

It was also found necessary to position the poise weight in relation to the beam fulcrum so that no inertia effects were detectable, otherwise instability and consequent "hunting" was produced. The poise weight

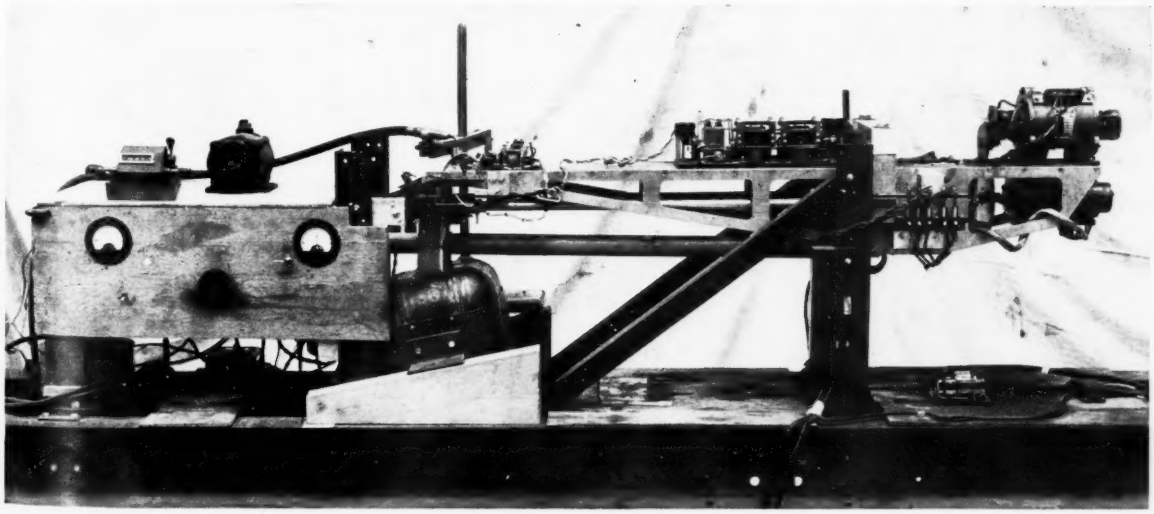

FIGURE 4. Experimental weighbeam used during development.

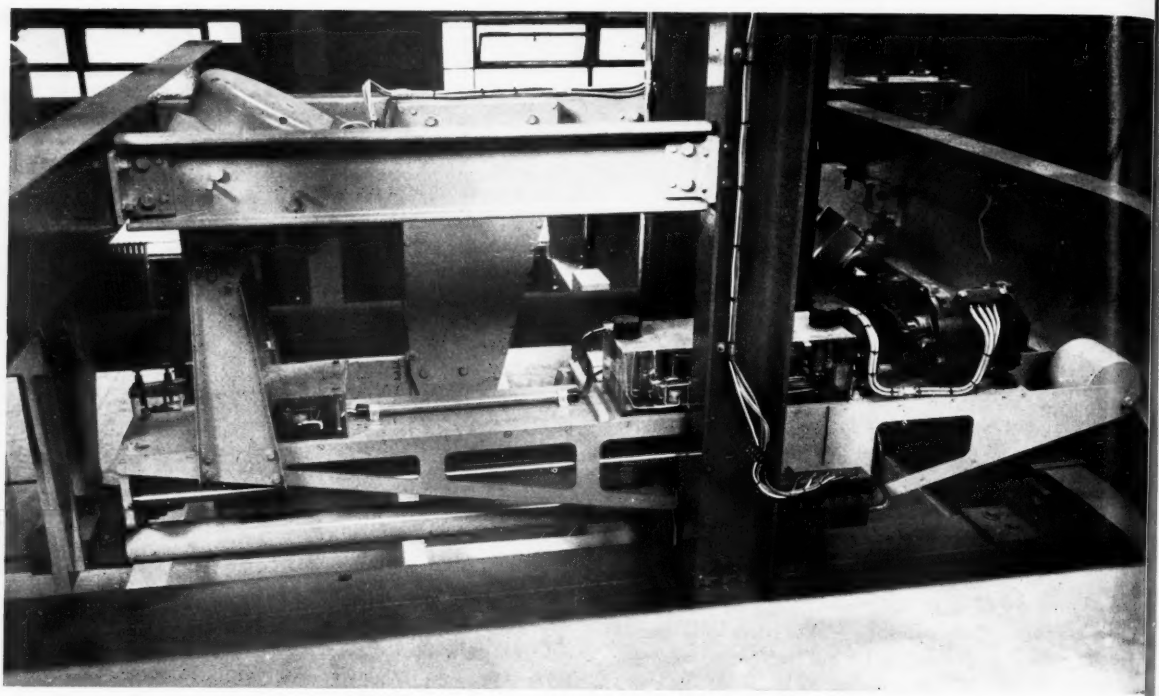

FIGURE 5. Drag weighbeam unit installed in the balance.

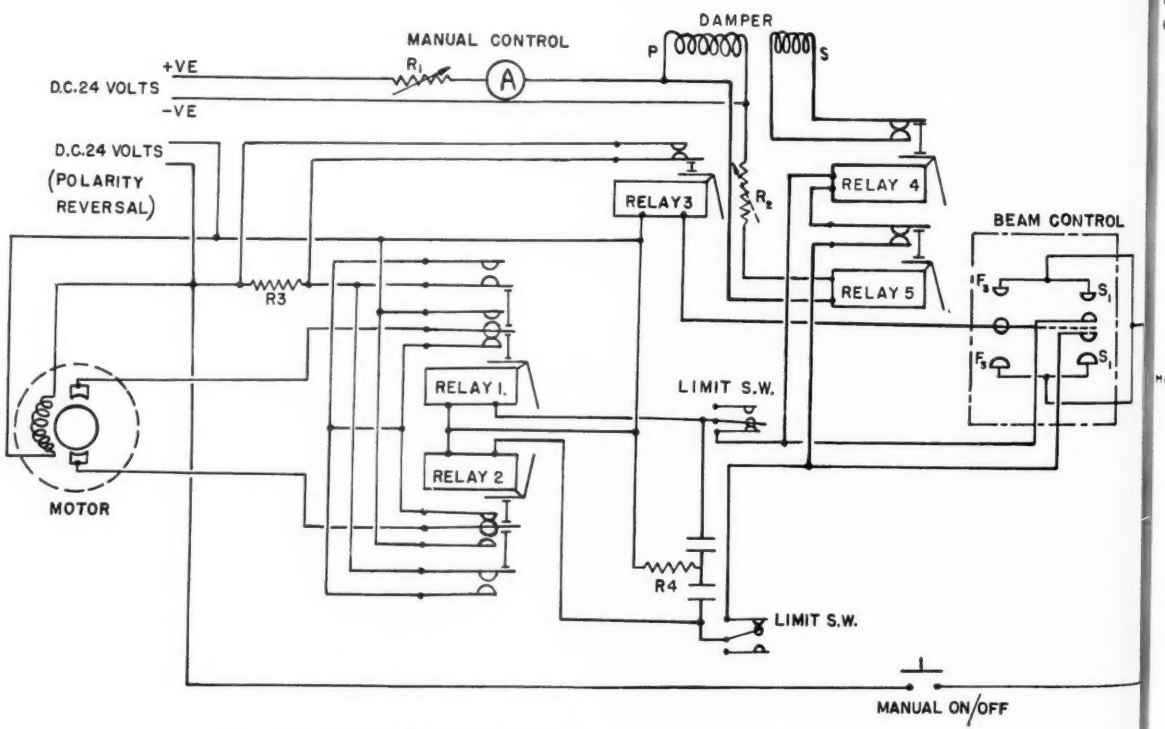

FIGURE 6. Circuit diagram of automatic weighbeam unit and damping system.

carries dowels on to which the doubling weight may be fitted for special tests, as mentioned in Section 2.2.

A weighbeam in its final form, installed in the balance, is shown in Fig. 5. It will be seen that the design has been cleaned up considerably over that of the experimental beam. The transparent plastic dust covers over the relay packs should be noted and also the mercury cups through which the various power supplies are fed into the beam.

Details of the electrical control circuit on each beam are shown in Fig. 6, from which the switching arrangements may be seen, and also the arrangement for ensuring satisfactory damping as discussed in Section 4.5.

4.3. WEIGHBEAM CONTACTS

The contacts are mounted on a light beryllium copper leaf spring, so that as the weighbeam floats into the equilibrium position, the spring deflection decreases to zero, and the contacts open circuit. The double pole contact assembly consists of a single pole change-over pair of silver and a single pole change-over pair of copper palladium alloy. Silver as a contact material is commonly used for light work where sensitivity is not required, this material being used for the high-speed contacts. Final balance at low speed is controlled by the copper palladium contacts whose principal characteristics are high contact sensitivity with low wear. Both sets of contacts carry only a small current of about 8 volt amps, sufficient to operate the motor relays. These relays, situated on the beams, are suitably spark-quenched, and consequently there are no burning or arcing troubles at the contacts due to the slow movement of the beams.

FIGURE 8. Coils and plunger of weighbeam indicator.

4.4. WEIGHBEAM INDICATORS

It was felt that with remote operation of a balance of this type in which the beams are not visible to the operator, some form of weighbeam position indicator was necessary, even though a self-balancing beam was used, to act as a check on the correct functioning of the balance and to ensure that readings are only taken when the beams are in the centralised position. For this purpose a small galvanometer fed from a rectified a.c. bridge circuit, without the need for amplification, is used on each beam. The indicating system depends upon a change of inductance in the two halves of a coil and is essentially an inductance bridge. The transmitter gives no bias to the beam, but accurately indicates its position to a remote station, the swing of the beam being reproduced by the swing of the galvanometer needle. The circuit used in this device is shown in Fig. 7, and the miniature coils and plunger are shown in Fig. 8.

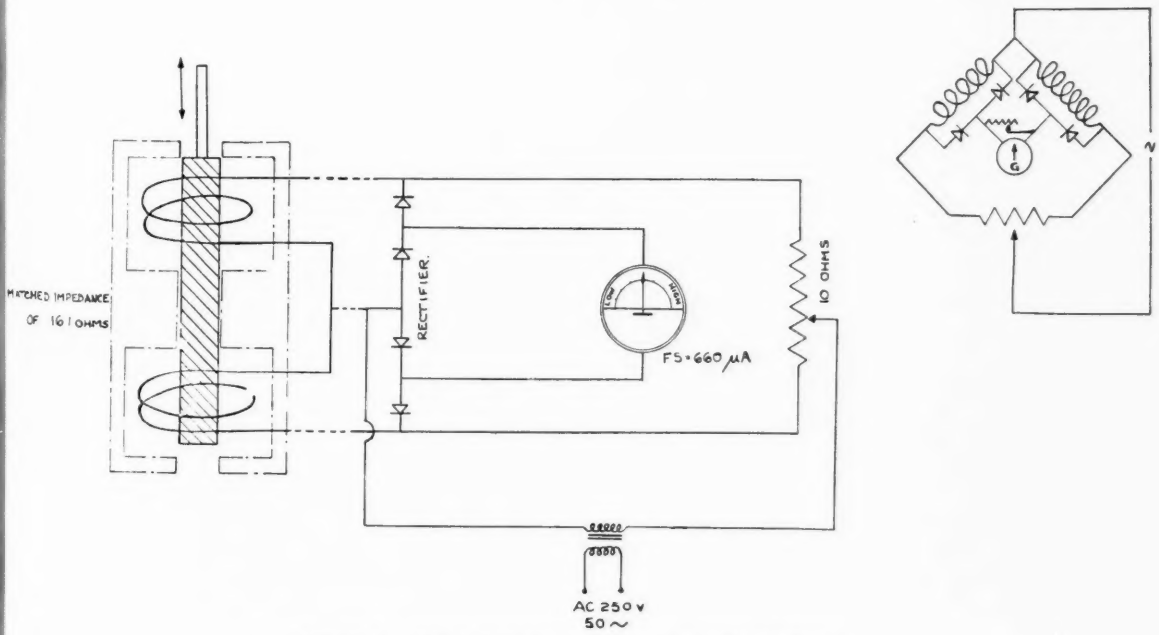

FIGURE 7. Circuit diagram of weighbeam position indicator.

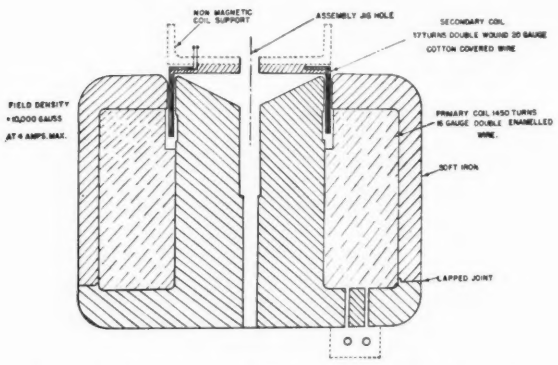
NON MAGNETIC COIL SUPPORT
ASSEMBLY JIG HOLE
SECONDARY COIL
17 TURNS DOUBLE WOUND 20 GAUGE COTTON COVERED WIRE
FIELD DENSITY 10,000 GAUSS AT 4 AMPS. MAX.
PRIMARY COIL 1450 TURNS 16 GAUGE DOUBLE ENAMELLED WIRE.
SOFT IRON
LAPPED JOINT

FIGURE 9. Section through electro-magnetic damping unit.

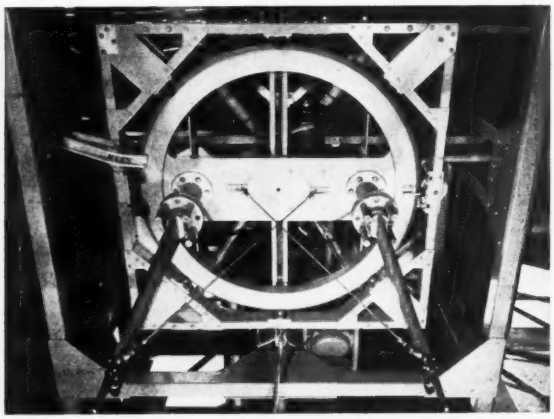

FIGURE 10. View of turntable and model support arms from below.

4.5. DAMPING

To take measurements in the region of the stall when the loads are subject to violent oscillations, it is necessary to provide some form of variable frictionless damping. In the present balance this is obtained magnetically by means of a moving coil attached to the weighbeam, working in the field of a powerful electro-magnet. In a similar, but earlier application, a solid copper disc had been used in place of the moving coil, but the weight of the disc, and consequent inertia effects, proved too great for the present beams, leading to instability of operation. The damping coils are shown in Fig. 9, in which the weight of the moving coil is only a few ounces. The primary coil consists of 1,450 turns of 16 S.W.G. copper wire, wound as a formerless coil and encased in soft iron, while the secondary coil carries 17 turns of double wound 20 S.W.G. wire. The required degree of damping was determined on the experimental beam, shown in Fig. 4, by means of a range of forced oscillations at various frequencies and strengths provided by a compressed air jet impinging on the beam. The greatest strength of the forced oscillation was taken as equivalent to 10 per cent. of the maximum lift force and was applied over a frequency range down to 0.5 cycles/sec., *i.e.* the jet was held on one second and then off one second. At frequencies greater than this, the inertia of the system coupled with the damping is sufficient to prevent "hunting," while at lower frequencies there is little difficulty in taking a mean reading on the balance counter. Naturally, the situation is greatly improved when the fluctuating load is less than the rather high value given. These limits are quite arbitrary as a damping strength requirement, but the present scheme has proved to be satisfactory in practice.

The design of the pole piece is such that the maximum strength of magnetic field is concentrated at the moving coil, and the annular magnetic field has a maximum density of 10,000 gauss at 100 watts loading

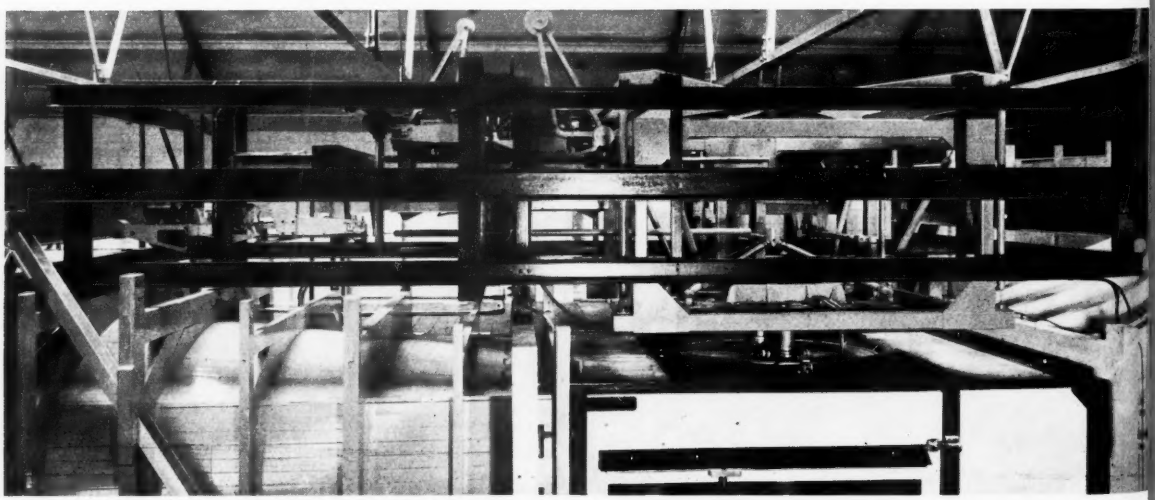

FIGURE 11. Side elevation of wind tunnel balance.

The degree of damping may be varied by means of a rheostat in the primary coil circuit without affecting the weighbeam equilibrium. It should be noted that the beams are largely of light alloy construction and that, if made of steel, screening may be necessary. It is now thought that the strength could be increased still further, without increasing the overall size of the damping unit, by a small change in the secondary coil windings.

The damping is only effective when the ends of the secondary coil are joined to form a closed circuit, and this fact has been utilised to assist in giving satisfactory stability to the beams. When the poise weight is in motion seeking the equilibrium position the secondary coil circuit is broken by means of a relay operated by the beam contacts. Under these conditions the beam has minimum or zero damping and there is no tendency to dwell on the contacts which would result in over-riding of the equilibrium position. However, as soon as the beam floats into the balanced position between the contacts, the secondary coil circuit is made, and the beam damped, thus enabling a high degree of sensitivity to be maintained without the onset of "hunting."

There are occasions when it is necessary to protect the weighbeams from extremely turbulent tunnel conditions, where sensitive measurements are not required. To cover such conditions it is arranged that the damping is made continuous when the control rheostats are turned beyond the 0·75 full damping position. The way in which the damping circuit is wired in conjunction with the beam contacts may be seen in Fig. 6.

5. Detail Design

Figure 10 shows a view of the model arms and turntable from below. The arms are spigoted into extensions of the turntable for rotation of the arms in yawed flight conditions. As originally designed the arms were of cantilever construction and circular section to avoid the complication of rotation, but the larger streamlined fairings, necessary to shield these arms from the air stream, introduced a marked local static pressure rise in the tunnel working section and they were consequently discarded in favour of the present slimmer, braced arms, and their associated smaller fairings, at a slight cost in tare drag.

The turntable, machined from a light alloy forging in D.T.D. 683, chosen for its wearing properties, is located by heavy duty ball bearings, running on the inclined faces of the turntable periphery. An endless roller chain fitting between these faces engages with the sprocket seen to the right of Fig. 10.

The general construction of the moment and force frames from rectangular seamless steel tubing is also apparent. A bolted-up construction using fitted bolts and distance tubes was used, to avoid the risk of distortion due to welding.

A side elevation of the balance is shown in Fig. 11, in which many of the main components may be seen. The balance mechanism may be picked out from the earth frame by its light grey enamel finish. The balance is fairly compact, the headroom between the tunnel and

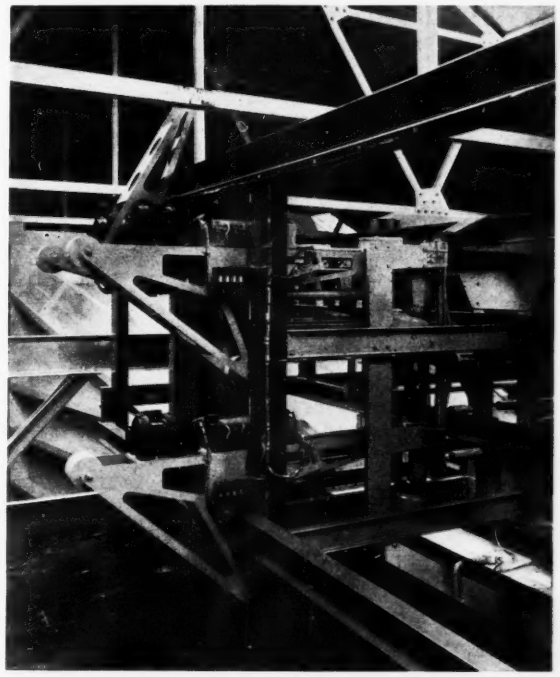

FIGURE 12. View of drift and rolling moment weighbeams.

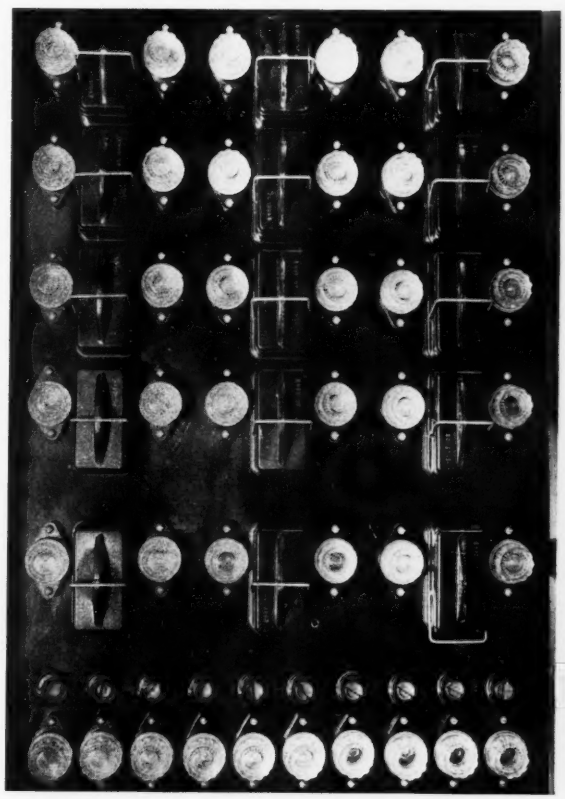

FIGURE 13. Self-indicating fuse panel.

the roof trusses being about 4 ft. 6 in. A view of the drift and rolling moment weighbeams showing the take-out mechanism, the counterpoise and stability weights, and other details common to all six systems, is given in Fig. 12.

It was found that, despite careful manufacture of detail parts, the small dimensional discrepancies which are inevitable in a structure of this kind can seriously impair its accuracy. Fortunately, provisions had been made for the easy adjustment of all lever lengths and other dimensions affecting the geometry, and this undoubtedly avoided undue delay in the initial calibration. Especially is this true of the inclined members forming the "virtual centre" mechanism, which are adjustable for length and inclination. The correct alignment of the virtual centre was obtained by the use of extension jigs clamped to the inclined links, by which means the effective centre line of each member was extended to meet at the moment centre. As an example of the care necessary here, the deflection of the jigs under their own weight was measured and allowed for in the setting-up process.

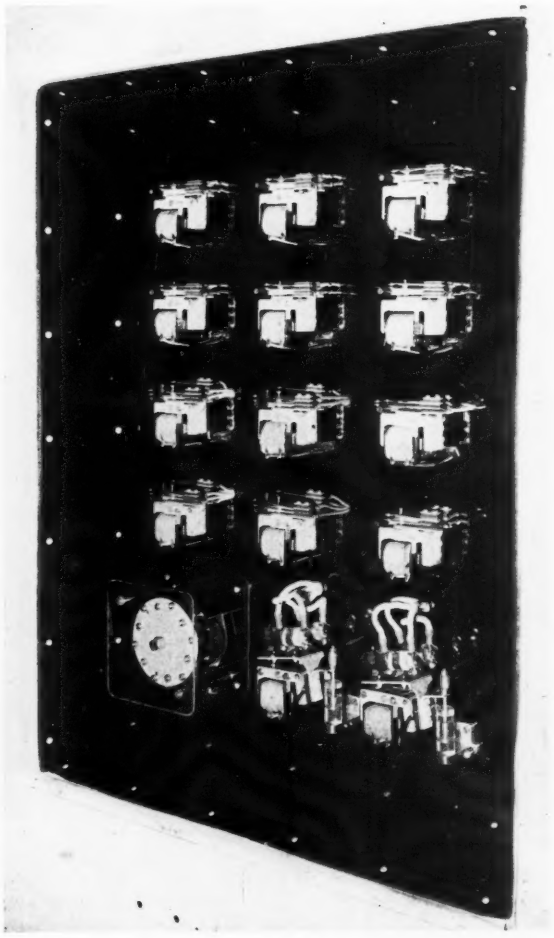

FIGURE 14. Interlock panel with polarity reversal mechanism.

6. Stability

A balance of the overhead type is inherently stable and, to increase the sensitivity, destabilising masses are usually required in addition to the counterpoise weights.

These have been placed above the weighbeam fulcrum, where necessary, to take advantage of the favourable leverage available, and thus reduce the size of weights required.

The dynamic stability of the balance is largely a matter of careful weighbeam design, as "hunting" is an ever present problem when a high degree of sensitivity is required, as discussed in Section 4.5.

7. Electrical Requirements

A choice lay between electronic and electro-mechanical systems for the operation of the automatic weighbeams, and as already described, an electro-mechanical system has been used. After some experimental work with various relay circuits, it was shown that the required response and reliability could be achieved by relatively simple methods.

The entire electrical circuit is composed of six principal sections:—

1. Power supply.
2. Self indicating fuse and interlock panel.
3. Weighbeams, dampers and "Selsyns."
4. Pitch and yaw motor circuits.
5. Auxiliaries, including high-speed slipstream motors.
6. Console controls.

The weighbeams have already been described in Section 4, and the auxiliaries form no part of the present paper.

7.1. POWER SUPPLY

Three sources of power are required for the balance:—

(*i*) Direct current 24 volts supplied by a 2·5 kilowatt generator with voltage stabilised to $\pm 0{\cdot}5$ volts under all conditions of load.

(*ii*) Direct current 24 volts tapped from this generator, but with periodic polarity reversal, generated by equipment in the balance itself.

(*iii*) Single-phase alternating current at 230 volts, tapped from the D.C. generator starter switch when locked in the "Delta" running position.

Requirement (*iii*) ensures that all three circuits are switched concurrently by a single Ellison starter. With the interlocks described in Section 7·2, it ensures that the poise weights do not get out of step with the counters, due either to the switching in of the separate supply systems at different times, or to an internal fault in the weighbeams.

7.2. FUSE AND INTERLOCK PANELS

From the generator panel, power lines run to the fuse panel, part of which is shown in Fig. 13. Self-indication of a component fault is obtained by shunting a small lamp across the fuse terminals. Consequently, a short circuit or fault to earth, blowing the fuse, will

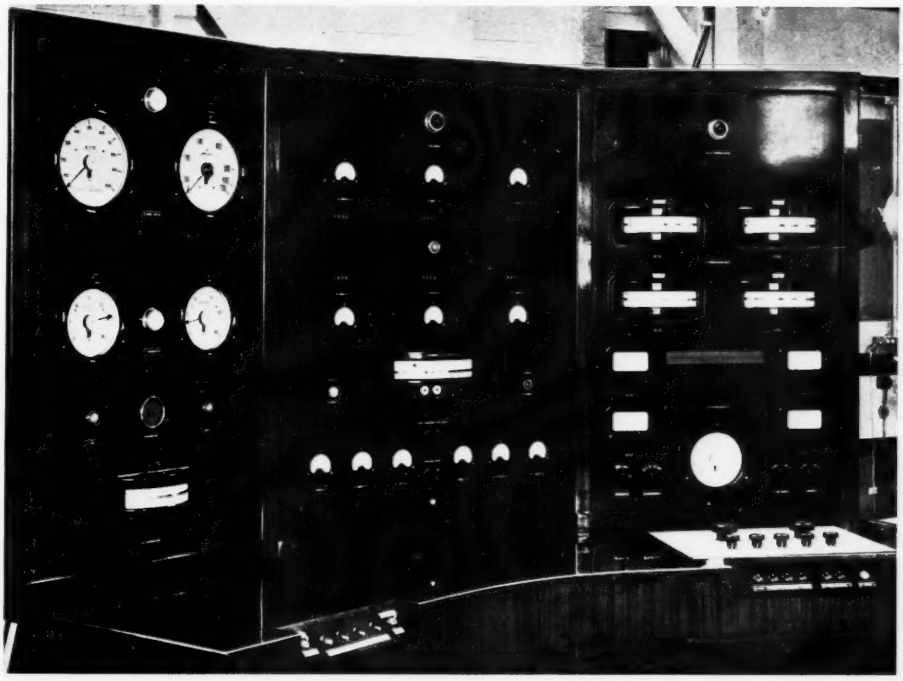

FIGURE 15. Wind tunnel balance control console.

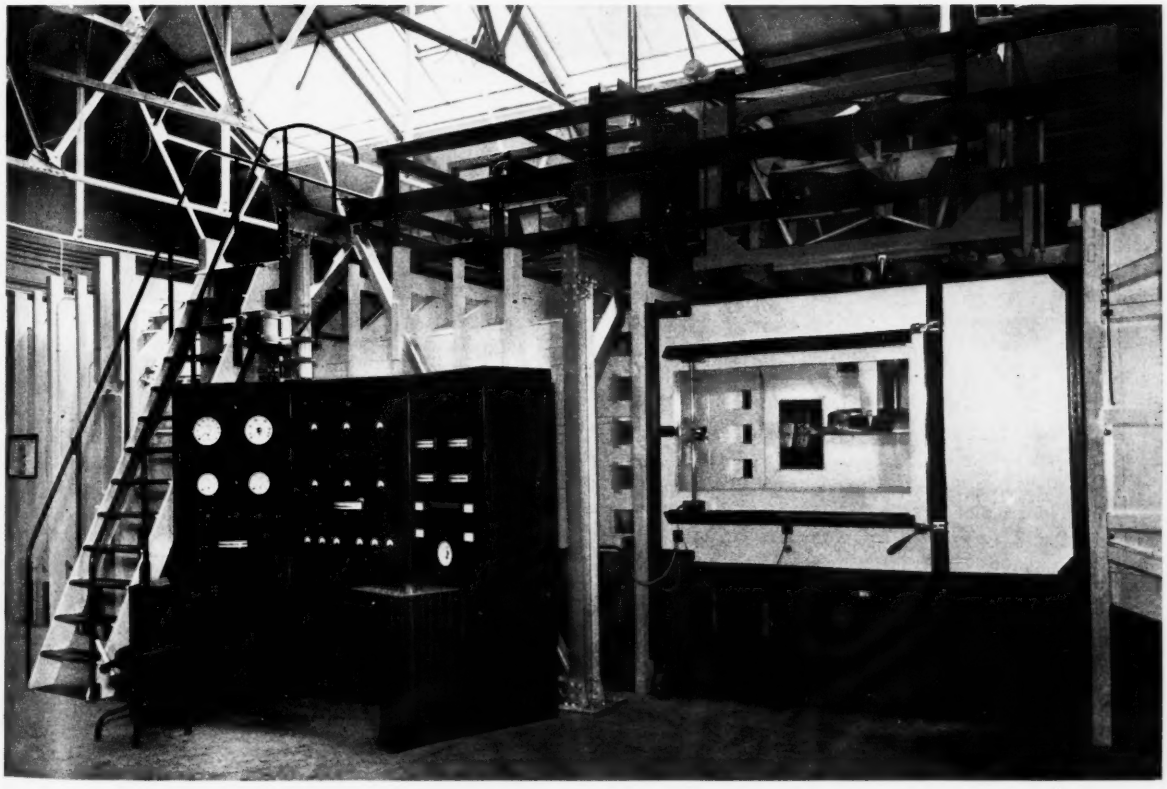

FIGURE 16. The complete balance and console installed in the 7 ft. × 5 ft. wind tunnel at Brough.

develop the supply potential across these terminals and will light the appropriate indicator lamp. Failure due to an open circuit is also shown by shunting a lamp across a small current resistance in the fuse line. Finally, an incipient fault detector in the D.C. system is obtained by an earth tapping between two indicator lamps arranged in series across the supply line. This scheme of fault indication shows immediately the component and type of failure and permits the use of semi-skilled labour for rectifying faults, as well as being a great saving in time.

The interlock panel is shown in Fig. 14 and carries the isolating relays and the D.C. polarity reversal mechanism. There are six isolators, one to each beam, and by suitable linking to the fusing system they automatically cut out the particular section in which a fault develops. It is possible, therefore, to replace a component while the remainder of the balance is in operation. The control relays in the pitch and yaw winch systems are also shown.

In the bottom left-hand corner of Fig. 14 may be seen the self-starting time-based polarity reversal mechanism, which operates the two heavy-duty double-pole mercury switches on the right of the timing mechanism. Every two working hours the polarity of the D.C. supply to the beams is reversed. It has been found that, by this means, the life of the contacts has been increased from about six months to four years or more without attention.

7.3. PITCH AND YAW MOTOR CIRCUITS

Control over the angles of incidence and yaw of the model is obtained by the two electrical winches shown on the moment frame of the balance in Fig. 10. Both motors are remotely controlled from relays housed in the interlock panel, and are operated by the finger buttons situated in the base of the incidence-setting telescope. For yaw control a suitable interlock prevents the model being yawed when the balance turntables are clamped in the operating condition while conversely, with the turntable unclamped, the weighbeams are rendered inoperative.

8. Balance Console

All controls and instruments associated with the operation of the wind tunnel, are mounted on the console shown in Fig. 15. The side panels are devoted to the main tunnel motor and the auxiliary power supplies, including those associated with the high-speed variable-frequency motors used in powered model tests.

On the centre panel are grouped the six beam indicators, counters and damping regulators necessary for the operation of the balance, while all the weigh-beam circuits are operated from a single central switch

The complete balance and console installation is shown in Fig. 16.

9. Calibration

The balance was calibrated by means of dead weight and a system of pulleys, using a special test bar attached to the model support arms.

At least the same standard of accuracy is necessary in the calibrating apparatus as in the balance itself and 2,000 lb. of dead weight, in suitable units, was made up, each unit being accurate to better than one part in 20,000, to avoid large accumulative errors. The test bar, which was provided with spherical self-aligning pick-up points, was made to comparable standards, and together with the specially selected ball-bearing mounted pulleys, provided a simple and reliable calibrating rig.

The calibration was carried out on each system in turn with the other five unloaded, and any interferences were noted. The procedure was then repeated with the five systems in the fully-loaded condition, to check that no change in calibration or interference effects occurs due to deflections under load. The balance behaves in a satisfactory manner under all conditions of loading and, despite the elastic deflections noted in Section 3.4, the accuracy is at all times within the limits set out in Section 2.1.

Despite great care in assembly, small interference effects were present in the initial calibration, but it was found possible to eliminate these systematically by small adjustments to the lengths of the various levers and links for which provision has been made.

For normal test purposes the residual interferences have finally been reduced to negligible proportions, but in cases where extreme accuracy is required it was found that five out of the thirty possible interference derivatives were still detectable. However, they are only detectable when large asymmetric forces and moments are present and, as they are linear in character, they can be readily allowed for where necessary.

10. Conclusion

The Blackburn six-component wind tunnel balance has proved to be a satisfactory and reliable piece of equipment eminently suitable for routine testing in a modern industrial tunnel and it is thought that it has certain advantages over other equipment of a similar nature installed in recent years.

The six components can be read off in a matter of 30 seconds and a complete test run occupies about 10 minutes and employs only two operators for the running of the tunnel. This results in economy of both labour and tunnel running time.

ACKNOWLEDGMENTS

The authors are indebted to Dr. W. S. Coleman for his valuable collaboration during the design and construction of this equipment and to Blackburn and General Aircraft for permission to publish the information given and for the use of the illustrations and photographs. The opinions expressed are those of the authors only.

Unsymmetrical Bending and Bending Combined with Axial Loading of a Beam of Rectangular Cross Section into the Plastic Range

by

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SUMMARY:—This note considers two cases of bending beyond the limit of proportionality which have not received a great measure of attention in the past. These are Case (*i*). A beam subjected to a pure bending moment acting in a plane other than one of symmetry. Case (*ii*). A beam subjected to a bending moment and an axial load.

A mathematical form is used for the stress-strain curve in order that the results shall be applicable to a large number of materials and to avoid the tedious arithmetical summations which would be necessary if actual stress-strain curves were used. All the results are presented in terms of form factors since this notation is convenient for design purposes and is consistent with current British practice. Although the method adopted in the analysis is applicable to a number of different types of beam cross section, only rectangular cross sections are considered in detail at the present time.

Curves are presented showing the variation of the form factor with respect to the angle of the plane of loading, for Case (*i*), and with respect to the ratio of bending moment to axial load for Case (*ii*). These curves are based upon a standardised form of the stress-strain curve which may be taken as representative of a range of aircraft materials. Consideration is given to the automatic satisfaction of present military proof loading requirements when these form factors are used for the estimation of maximum permissible bending moments and axial loads under ultimate loading conditions.

The recommendations of F. P. Cozzone,[1] for dealing with these two problems are examined and comparison is made between the theoretical work of this note and a limited number of test results available for Case (*i*).

1. Introduction

The solution of problems concerning the bending of sections beyond the limit of proportionality is usually brought about by processes of arithmetical summation applied to actual stress-strain curves. The procedure is straightforward when the position of the neutral surface is known or can reasonably be assumed to be in a certain position. When this position is unknown, as with pure bending other than about an axis of symmetry or with bending combined with axial loading, the same method could still be applied but would require working from a series of assumed neutral surface positions. The tedium of this process may account for the lack of published information on these problems.

Generalised relations may be set up fairly simply for bending moment and axial load if a mathematical expression is used instead of an actual stress-strain curve. A suitable form for this purpose is

$$\varepsilon = A\left(\frac{f}{f_2}\right) + B\left(\frac{f}{f_2}\right)^n . \quad . \quad . \quad (1)$$

This expression can be made to give a very close representation of actual stress-strain curves of many materials, at least up to the 0·5 per cent. proof stress. It was previously used and discussed in Ref. 2.

The principal assumptions made in this paper are the same as those made in a previous note[2].

Received April 1953.

Notation

x, y	rectangular co-ordinate system coinciding with the principal axes of the beam cross section
y_1	ordinate of the neutral surface in Case (*ii*)
b, D, w', z'	dimensions of the cross section (*see* Figs. 1 and 2)
e	eccentricity of axial load from centroid of section
I_{XX}, I_{YY}	section moments of inertia with respect to the x- and y-axes
Z_{XX}, Z_{YY}	sectional moduli with respect to the x- and y-axes
A, B, n	constants in equation (1)
f	stress
F	f/f_2
ε	strain
E	modulus of elasticity
α	angle between the plane of the applied loading and the y-axis

θ angle between the neutral surface and the x-axis

$\Phi_0, \Phi_1, \Phi_2, \Phi_3$ functions defined in the table of Appendix I

M bending moment

P axial load

K form factor

Special Suffixes

A, B, C referring to points A, B of Fig. 2 and C of Fig. 6

E elastic distribution of stress

e appropriate to an axial load offset by e from the centroid of the cross section

$1, 2, 5$ appropriate to the 0·1, 0·2 and 0·5 per cent. proof stresses

m maximum

α appropriate to a plane of loading at an angle α to the y-axis

2. Case (*i*)

2.1. MATHEMATICAL ANALYSIS

In elastic bending when the plane of the applied bending moment is not parallel to a principal axis of the cross section to which it is applied, the neutral surface ceases to be at right angles to the plane of applied loading. This phenomenon, generally considered under the title of unsymmetrical bending, has a simple solution leading to the well-known expressions

$$M_{\alpha E} = \frac{f_m}{\frac{\cos \alpha}{Z_{XX}} + \frac{\sin \alpha}{Z_{YY}}} \quad . \quad . \quad . \quad (2a)$$

$$\tan \theta_E = \frac{I_{XX}}{I_{YY}} \tan \alpha \quad . \quad . \quad . \quad . \quad (2b)$$

When the maximum stress exceeds the limit of proportionality for the material of the beam these expressions are no longer applicable. The change brought about by a non-elastic distribution of stress may be examined by reference to Fig. 1(*a*).

The rectangular cross section $ABCD$ is subjected to a moment $M_{\alpha E}$, acting in a plane at an angle α_E to the y-axis. Under this loading, if the stresses remain within the material limit of proportionality, the neutral surface takes up a rotation θ_E to the x-axis. With the usual assumption of a linear distribution of strain over the cross section, the stress distribution may be represented by the dotted line of_m and a strip such as GH (parallel to the neutral surface) sustains a uniform stress across the width. The contributions of such a strip to the components of the bending moment M_{XXE} and M_{YYE} may be considered as the load on the strip multiplied by the y and x moment arms of the centre of area of the strip. The locus of centres of area for all such strips making up the half cross section is given by the line OFA.

If a non-elastic distribution of stress (as shown by the full line of_m) is substituted for the elastic distribution, the stress across each strip is increased. For a strip such as GH, for which the x and y moment arms are non-zero, the increased contributions to M_{XX} and M_{YY} remain in the same proportion as the contributions to M_{XXE} and M_{YYE} under the elastic distribution. However, for a strip such as JK, in which the value of the x moment arm is zero, no increased contribution is made to M_{YY} although there is an increased contribution to M_{XX}. Summing these effects over the whole cross section, the ratio M_{XX}/M_{YY} for the non-elastic distribution is greater than the corresponding ratio M_{XXE}/M_{YYE} for the elastic distribution. Therefore the neutral surface rotation θ_E now corresponds to a rotation α of the plane of loading which is smaller than the rotation α_E for an elastic distribution. This is illustrated in the vector diagrams 1(*b*) and 1(*c*).

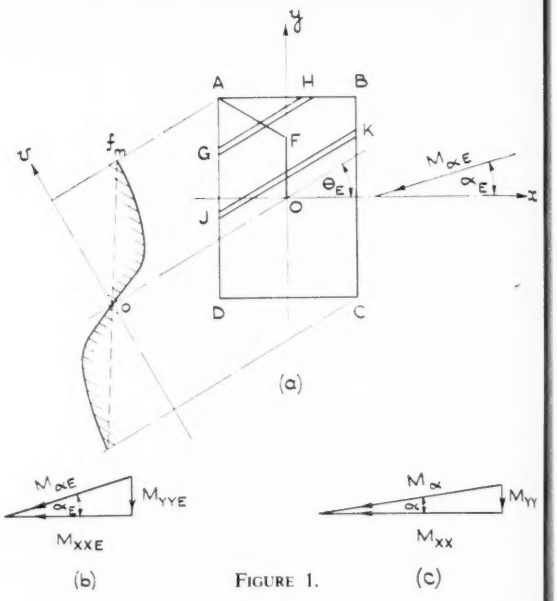

FIGURE 1.

For a given angle of the plane of loading, the neutral surface for a non-elastic distribution of stress is rotated farther than it would be if the stress distribution were elastic, in the particular configuration of Fig. 1. When the neutral surface lies in the diagonal DB the x and y moment arms of all strips are non-zero, since the locus of centres of area of strips parallel to the neutral surface is a line OA, and α for the non-elastic distribution is equal to α_E for the elastic distribution. By a similar reasoning it may be shown that when the neutral surface has rotated beyond DB, for a given angle of the plane of loading, the rotation of the neutral surface is less for a non-elastic stress distribution than for an elastic distribution.

Having shown that the neutral surface rotation is itself dependent upon the type of stress distribution, the permissible applied bending moment M_α and the neutral surface rotation θ will be evaluated for a rectangular section beam in a material having a stress-strain curve represented by equation (1).

Considering strips taken parallel to the neutral surface (*see* Fig. 2):—

$$M_{XX} = 2 \int_0^{v_A} fw' y dv \quad . \quad . \quad . \quad (3a)$$

$$M_{YY} = -2 \int_{v_B}^{v_A} fw' x dv \quad . \quad . \quad . \quad (3b)$$

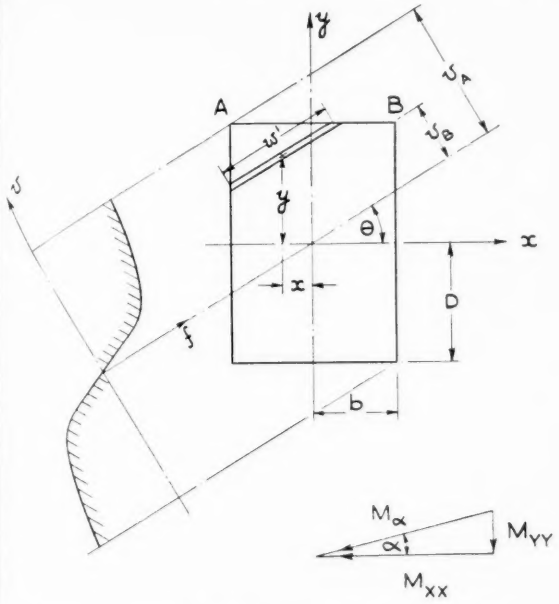

FIGURE 2. Unsymmetrical bending of a rectangular beam.

The following *geometrical relationships* are used:—

$$y=\frac{v}{\cos\theta} \qquad 0<v<v_B$$

$$y=\frac{v+v_B}{2\cos\theta} \qquad v_B<v<v_A$$

$$x=0 \qquad 0<v<v_B$$

$$x=\frac{v_B-v}{2\sin\theta} \qquad v_B<v<v_A$$

$$w'=w=\frac{2b}{\sin\theta} \qquad 0<v<v_B$$

$$w'=\frac{v_A-v}{\sin\theta\cos\theta} \qquad v_B<v<v_A .$$

From the assumption of linear strain variation along the v-axis and working to a maximum fibre strain of ε_5, the following *stress-strain relationships* are derived:

$$v=v_A\frac{\varepsilon}{\varepsilon_5}$$

$$dv=\frac{v_A}{\varepsilon_5}\left\{\frac{A}{f_2}+\frac{nB}{f_2}\left(\frac{f}{f_2}\right)^{n-1}\right\}df .$$

$$\text{at } v=v_A ; \quad f=f_5$$

$$\text{at } v=v_B ; \quad f=f_B .$$

$$\frac{v_B}{v_A}=\frac{\varepsilon_B}{\varepsilon_5}=\frac{1-\dfrac{b}{D}\tan\theta}{1+\dfrac{b}{D}\tan\theta} .$$

Substituting these expressions into equations (3*a*) and (3*b*) gives the following expressions after integration and reduction:—

$$\frac{M_{XX}}{4f_2bD^2}=\frac{2}{(\varepsilon_5+\varepsilon_B)^2}\left\{\Phi_0+\Phi_1+\frac{\varepsilon_B\Phi_3-\varepsilon_5\Phi_2}{\varepsilon_5-\varepsilon_B}\right\} \qquad (4a)$$

$$\frac{M_{YY}}{4f_2b^2D}=\frac{2}{(\varepsilon_5-\varepsilon_B)^2}\left\{\Phi_1-\Phi_0+\frac{\varepsilon_B\Phi_3+\varepsilon_5\Phi_2}{\varepsilon_5+\varepsilon_B}\right\} \qquad (4b)$$

Φ_0, Φ_1, Φ_2 and Φ_3 are functions of F_B, F_5 and the material constants A, B and n (*see* Appendix I).

The resultant bending moment M_α and the appropriate angle of the plane of loading α may now be found.

$$M_\alpha=(M_{XX}^2+M_{YY}^2)^{\frac{1}{2}} \qquad . \quad . \qquad (5)$$

$$\tan\alpha=\frac{M_{YY}}{M_{XX}} . \qquad . \quad . \quad . \qquad (6)$$

For convenience of application of these results a form factor, K_α, is used, and is defined by

$$M_\alpha=K_\alpha f_2 Z_{XX} \qquad . \quad . \quad . \qquad (7)$$

in which M_α is the maximum permissible bending moment applied in a plane at an angle α to the y-axis of the beam.

K_α has been calculated for rectangular beams, of various depth to width ratios, in a standardised material representative of a large number of actual materials used in aircraft structures. These results are plotted in Fig. 3. The material is that represented by the asterisk on Fig. 3 of Ref. 2 and has coefficients appropriate to the form of the stress-strain curve of equation (1) as follows:—

$$E/f_2=250 , \quad f_5/f_2=1{\cdot}050 , \quad A=0{\cdot}004 ,$$
$$B=0{\cdot}002 , \quad n=18{\cdot}78 .$$

In Ref. 2, some justification was given to the estimation of maximum permissible bending moments in rectangular sections based upon the 0·5 per cent. proof stress in order to ensure automatic satisfaction of current military proof-loading requirements. The arguments presented in Ref. 2 are applicable in the present case when $\alpha=0°$ and when $\alpha=90°$.

For other angles of the plane of loading a greater proportion of the material of the cross section enters the elastic range and it is concluded that maximum permissible bending moments based upon the same maximum fibre stress will be satisfactory from the proof-loading aspect for rectangular sections bending other than about an axis of symmetry.

Figure 4 shows the angle of rotation of the neutral surface in rectangular beams of various depth to width ratios in the standardised material and with the same maximum fibre stress used for the calculations leading to Fig. 3.

2.2. COMPARISON WITH OTHER RESULTS

Cozzone[1] gives some consideration to the problem of unsymmetrical bending and proposes that a straight line interaction be used between the stress ratios R_x and R_y where, in the notation of this paper, $R_x=M_\alpha\cos\alpha/M_{xx}$ and $R_y=M_\alpha\sin\alpha/M_{yy}$. M_{xx} and M_{yy} are the maximum permissible moments about the x- and y-axis respectively.

The interaction may be expressed as

$$1=R_x+R_y=\frac{M_\alpha\cos\alpha}{M_{xx}}+\frac{M_\alpha\sin\alpha}{M_{yy}} .$$

Using the notation of form factors and representing by K the form factor appropriate to $\alpha=0°$,

$$1=\frac{K_\alpha f_2 Z_{XX}}{f_2 K}\left(\frac{\cos\alpha}{Z_{XX}}+\frac{\sin\alpha}{Z_{YY}}\right)$$

$$\frac{K_\alpha}{K}=\frac{1}{\left(\cos\alpha+\frac{D}{b}\sin\alpha\right)}.$$

This proposal is compared with the present analysis on Fig. 5. The straight line interaction proposal is shown to be very conservative, especially for square or nearly square cross sections.

Experimental work on this problem is very limited. Ref. 3 reports a series of tests conducted by H. A. Williams at Stanford University on rectangular and other cross section beams in 75S-O material. This material was chosen in view of the supposed similarity between the tension and compression stress-strain curves. Control tests revealed, however, that there was a considerable difference in this respect, and for all calculation purposes Williams worked to a mean curve. The characteristics of this curve are $E/f_2=416$ and $f_5/f_2=1{\cdot}091$, the strain appropriate to the 0·5 per cent. proof stress being 0·0076. Three or four beams with $D/b=2$ were loaded by pure bending in each of four planes corresponding to $\alpha=0°$, 30°, 60° and 90°. Values of K_α, as defined in equation (7), for a mean strain of 0·0076 in the extreme fibres have been extracted from this work and the mean values are shown plotted as the circles on Fig. 5.

Figure 3 of Ref. 2 indicates that a beam having the material characteristics of the 75S-O mean stress-strain curve would have $K=1{\cdot}480$ when loaded in a plane of symmetry, whereas a beam in the standardised material used for the curves of Fig. 5 would have $K=1{\cdot}416$. To make an allowance for this difference in the material, the mean value of the experimental values of K_α at each value of α has been multiplied by a factor $1{\cdot}416/1{\cdot}480$. These modified values are plotted as the square points on Fig. 5 and the comparison between the present theory and experiment is quite good. Note that the correction made for differences in material should strictly only be applied at $\alpha=0°$ and $\alpha=90°$.

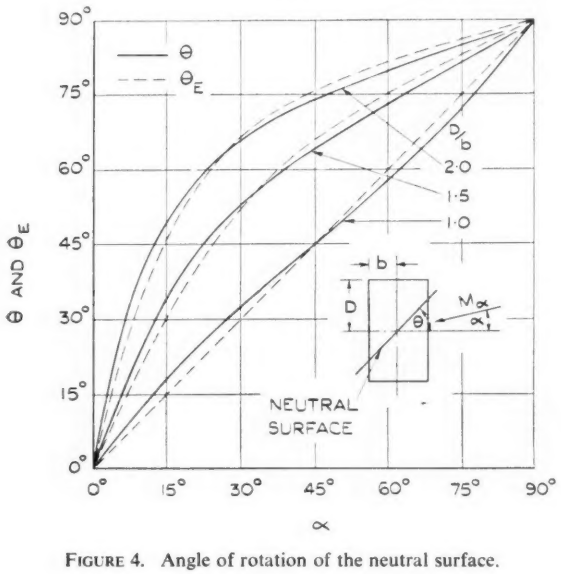

FIGURE 4. Angle of rotation of the neutral surface.

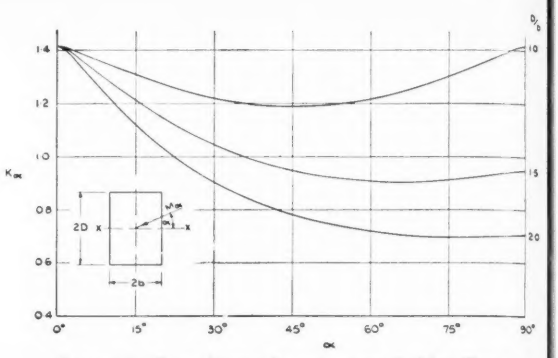

FIGURE 3. Form factors for unsymmetrical bending.

Williams[3] does not make any reference to Cozzone's proposal of a straight line interaction between the components of bending about the two axes of symmetry. An extension is made to the work of Cozzone, however, which gives good agreement with the experimental results for rectangular cross sections. The extension is based upon an approximation to the rotation of the neutral surface. The angle of rotation used is that calculated for an elastic distribution of stress. Fig. 4 shows that in the present case this is a fair approximation and should not, of itself, lead to a highly erroneous estimation of bending moment.

For completeness the expression evolved by Williams is given in Appendix II. The Cozzone intercept stress f_0 is also given in terms of Φ_0, and so on, *i.e.* in terms of the coefficients of equation (1), thus avoiding graphical evaluation.

3. Case (*ii*)

3.1. MATHEMATICAL ANALYSIS

Consider now a rectangular section subjected to a bending moment about an axis of symmetry and an axial load. The analysis is appropriate to short beams in which the possibility of an instability failure can be ignored.

Bending moment M_{XX} and axial load P give rise to a strain distribution (*see* Fig 6)

$$\varepsilon=\frac{y+y_1}{D+y_1}\,\varepsilon_5.$$

A maximum fibre strain of ε_5 has been assumed and will be given further consideration later.

It is found convenient to change the axes so that

$$x'=x$$
$$y'=y+y_1$$

and therefore $$\varepsilon=\frac{y'}{D+y_1}\,\varepsilon_5.$$

For $\left|\frac{y_1}{D}\right|\leqslant 1$:—

Moment about the axis $X'X'=$

$$M'_{XX}=\int_0^{D+y_1}2bfy'dy'+\int_0^{D-y_1}2bfy'dy'. \quad . \quad . \quad (8a)$$

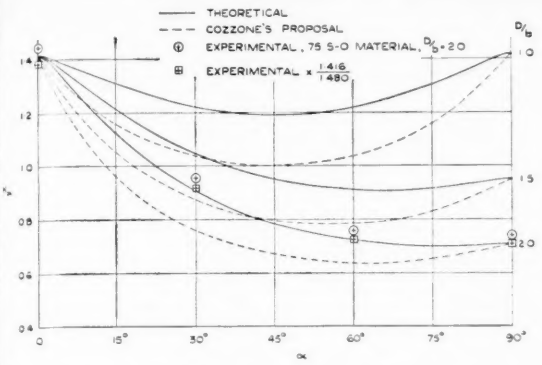

FIGURE 5. Comparison with experimental results.

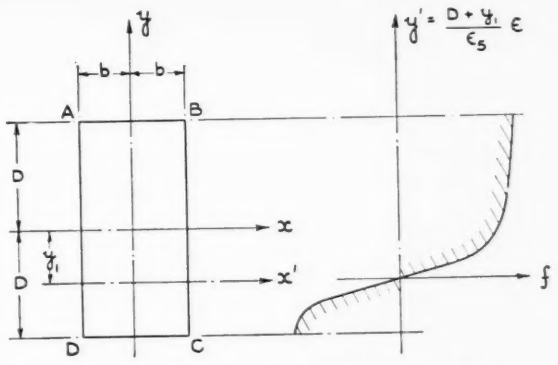

FIGURE 6. Stress distribution in a section subjected to bending moment and axial load.

$$\text{Axial load } P=\int_0^{D+y_1} 2bf\,dy' - \int_0^{D-y_1} 2b_i f\,dy' \quad . \quad . \quad . \quad (8b)$$

The following *stress-strain relationships* may be set up:—

$$y'=\frac{D+y_1}{\varepsilon_5}\,\varepsilon=\frac{D+y_1}{\varepsilon_5}\left[A\left(\frac{f}{f_2}\right)+B\left(\frac{f}{f_2}\right)^n\right].$$

At $y'=D+y_1$; $f=f_5$

at $y'=D-y_1$; $f=f_C$.

Substituting in equations (8*a*) and (8*b*) gives the following expressions, after integration and reduction:—

$$M'_{XX}=\frac{8bD^2f_2}{(\varepsilon_5+\varepsilon_C)^2}(\Phi_0+\Phi_1) \quad . \quad . \quad (9a)$$

$$P=\frac{4bDf_2}{(\varepsilon_5{}^2+\varepsilon_5\varepsilon_C)}\Phi_3 \quad . \quad . \quad . \quad (9b)$$

where Φ_0, Φ_1 and Φ_3 are given in the table of Appendix I with $F_C=f_C/f_2$ replacing F_B.

It is convenient to represent the combined moment and axial load by one load offset from the centroid of the beam by an amount e (*see* inset diagram on Fig. 7).

Then $$e=\frac{M'_{XX}-Py_1}{P}.$$

Using the strain relationship

$$\frac{\varepsilon_C}{\varepsilon_5}=\frac{D-y_1}{D+y_1}$$

and choosing a series of values of y_1, it is possible to calculate P, M'_{XX}, e and the moment about the centroidal axis, M_{XX},

where $$M_{XX}=Pe=M'_{XX}-Py_1 \quad . \quad . \quad . \quad (10)$$

Again using the form factor notation, a form factor K_e is defined by

$$M_{XX}=K_e f_2 Z_{XX} \quad . \quad . \quad . \quad (11)$$

K_e has been calculated for maximum fibre stresses of f_5 and f_2 in the standardised material already used. These values are shown plotted on Fig. 7 as functions of e/D and are marked K_{e5} and K_{e2} respectively. The position of the neutral surface as represented by the ratio y_1/D is also plotted on Fig. 7 as a function of e/D and is appropriate to a maximum fibre stress of f_5.

In Ref. 2 it was shown that a maximum fibre stress of f_5, in the pure bending case at ultimate loading, automatically satisfied the current military requirement of a proof loading of 75 per cent. ultimate. The recommendation of A.P.970, for a pure tensile loading, is that the proof load should be based upon the 0·1 per cent. proof stress in tension. K_{e1} has been calculated for a maximum fibre stress of f_1 and the broken line on Fig. 7 represents $(4/3)K_{e1}$. It will be observed that below e/D of about 6 a maximum fibre stress of f_5 in the ultimate loading condition will not satisfy the recommendation of A.P.970 for pure tensile loading. Consequently, to give a conservative interpretation to the proof loading requirement, the curves *obcd* should be used as a guide for the estimation of combinations of maximum permissible bending moments and axial loads in rectangular sections when the axial load is tensile.

A.P.970 recommends that for pure compression the ultimate load should be based upon the 0·2 per cent. proof stress (except for magnesium base alloys) and suggests that satisfaction of proof-loading requirements will then follow automatically. It would therefore seem advisable to use the curve marked K_{e2} on Fig. 7 for guidance in the estimation of combinations of maximum permissible bending moments and axial loads in rectangular sections when the axial load is compressive and leads to low values of e/D. The possibility of an instability failure with compressive loading should also receive attention.

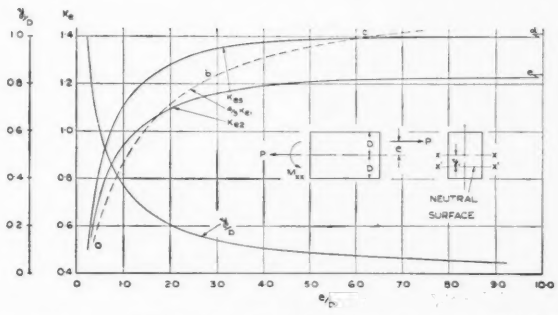

FIGURE 7. Form factors for a rectangular section subjected to combined bending moment and axial loading.

3.2. COMPARISON WITH OTHER RESULTS

For this case Cozzone again suggests that a straight line interaction be used between the stress ratios R_x, R_y and R_a where

$$R_a = \frac{\text{applied direct stress}}{\text{permissible direct stress}}$$

This interaction may be expressed as

$$1 = R_x + R_a \quad (R_y = 0).$$

For a maximum fibre stress f_5,

$$1 = \frac{K_c f_2 Z_{XX}}{K f_2 Z_{XX}} + \frac{K_c f_2 Z_{XX}}{4bDe} \times \frac{1}{f_5},$$

$$K_c = \frac{1}{\frac{1}{K} + \frac{1}{3}\frac{f_2}{f_5}\frac{D}{e}},$$

and for the standardised material $f_5/f_2 = 1{\cdot}05$ and $K = 1{\cdot}416$.

Therefore

$$K_c = \frac{1}{0{\cdot}706 + \dfrac{0{\cdot}317}{e/D}}.$$

Similarly for a maximum fibre stress f_2,

$$K_c = \frac{1}{0{\cdot}806 + \dfrac{0{\cdot}333}{e/D}}.$$

These lines are shown plotted in Fig. 8 with the results of the present investigation. Although it is somewhat conservative, Cozzone's proposal compares favourably with these results and might well be adapted for design purposes at least for rectangular sections.

No experimental results suitable for comparison with the theoretical work have come to light.

An interesting sidelight of this investigation concerns the placing of a load P on a rectangular bar so that there shall be no reversal of the sign of the stress across the section. From Fig. 7 it will be noted that $y_1/D = 1{\cdot}0$ at an e/D of 0·205 when the maximum fibre stress is the 0·5 per cent. proof value. For a maximum fibre stress of 0·2 per cent. proof, $y_1/D = 1{\cdot}0$ at e/D of 0·274. The well known "middle third" rule for an elastic material gives $y_1/D = 1{\cdot}0$ at e/D of 0·333.

Therefore, as the offset axial load increases beyond the value required to cause the stresses within the rectangular bar to exceed the limit of proportionality, an increasingly severe restriction is placed upon the eccentricity of loading if no reversal in the sign of the stress across the section is to be encountered. At a maximum fibre stress of the 0·5 per cent. proof value, in the chosen standardised material, a "middle fifth" rule would be more appropriate.

4. Concluding Remarks

4.1. CASE (*i*)

Curves have been presented from which the maximum permissible bending moment for a rectangular section beam may be estimated, when the plane of loading does not coincide with an axis of symmetry. Although these curves are strictly applicable only to the standardised material having the characteristics

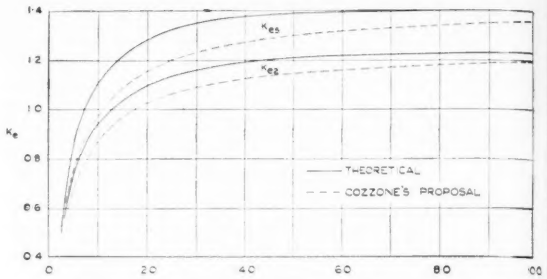

FIGURE 8. Comparison with Cozzone's proposal.

$f_5/f_2 = 1{\cdot}05$ and $E/f_2 = 250$, they may be used as a guide for most ductile materials used in aircraft work. If desired a correction could be applied to take account of different material characteristics by applying a factor $K/1{\cdot}416$ to the values K_a taken from Fig. 3. This value of K may best be found from Fig. 3 of Ref. 2.

A maximum fibre stress of the 0·5 per cent. proof has been used and satisfaction of current proof-loading requirements should follow automatically.

Comparison with the proposal of Cozzone, for a straight line interaction between bending components about the two axes of symmetry, has shown that the proposal is very conservative, especially for beams of square cross section.

A modification of the formulae developed by Cozzone has been made[3] and compares well with the test results of the same report. The approximation upon which the modification was based has been found reasonable in the light of the theoretical work of this note. The expressions appropriate to the proposed modification are given in Appendix II in terms of the coefficients of the mathematical form of the stress-strain curve. For a rapid estimation of the permissible bending moment in a rectangular beam of most materials used in aircraft structures, for a given rotation of the plane of loading, these expressions have their advantages over the more rigorous treatment presented herein.

4.2. CASE (*ii*)

Formulae have been developed from which may be derived the combinations of bending moment and axial load appropriate to a maximum fibre stress of 0·5 per cent. proof. Curves have been presented for various combinations of permissible axial load and bending moment in a standardised material and may be used as a guide for "stressing" purposes for most materials in common use. Note should be made of the modifications brought about to ensure automatic satisfaction of proof-loading requirements.

Cozzone's proposal of a straight line interaction in this case, although somewhat conservative, is probably satisfactory for most design purposes when applied to beams of rectangular cross section.

The method adopted in the analysis of this note could be applied in both Cases (*i*) and (*ii*) for other types of cross section, although the application of the results would probably become tedious. The presentation of these results in general form would also be

difficult in view of the large number of variables involved. However, it is quite possible that the use of simplifying assumptions, similar to those made by Williams for rectangular sections, would enable suitable approximate expressions to be developed.

Acknowledgment

The author wishes to acknowledge the general assistance rendered by Mr. D. C. Smith, Head of the Technical Department, in the preparation of this note.

APPENDIX I

THE FUNCTIONS Φ_0, Φ_1, Φ_2 AND Φ_3

	Φ_0	Φ_1	$\varepsilon_5\Phi_2$	Φ_3/ε_5
F_5^3	$A^2/3$			
F_5^{n+2}	$AB\dfrac{n+1}{n+2}$			
F_5^{2n+1}	$B^2\dfrac{n}{2n+1}$			
F_B^3		$A^2/3$		
F_B^{n+2}		$AB\dfrac{n+1}{n+2}$		
F_B^{2n+1}		$B^2\dfrac{n}{2n+1}$		
$F_5^2-F_B^2$				$A/2$
$F_5^4-F_B^4$			$A^3/4$	
$F_5^{n+1}-F_B^{n+1}$				$B\dfrac{n}{n+1}$
$F_5^{n+3}-F_B^{n+3}$			$A^2B\dfrac{n+2}{n+3}$	
$F_5^{2n+2}-F_B^{2n+2}$			$AB^2\dfrac{2n+1}{2n+2}$	
$F_5^{3n+1}-F_B^{3n+1}$			$B^3\dfrac{n}{3n+1}$	

Note: $F_5=f_5/f_2$, $F_B=f_B/f_2$, and other symbols have the meanings already assigned.

APPENDIX II

H. A. WILLIAMS'S ESTIMATION OF BENDING MOMENTS FOR CASE (*i*)

In Ref. 3, H. A. Williams develops the following expression for bending moment in the plastic range when the plane of applied loading does not coincide with a principal axis:—

$$M_\alpha=\frac{I_N}{c_N}\,\frac{1}{\cos(\theta_E-\alpha)}\,[f_m+f_0(k-1)]$$

where

c_N = distance of outer fibres of beam from the neutral surface (*see* Fig. 9)

I_N = moment of inertia of cross section with respect to the neutral surface

f_m = maximum fibre stress

ε_m = maximum strain

$$f_0=\text{Cozzone intercept stress}=\frac{6}{\varepsilon_m^2}\int_0^{\epsilon_m} f\varepsilon\,d\varepsilon-2f_m$$

$$k=\frac{2Q_m}{I_N/c_N}$$

Q_m = static moment of one half of the beam cross section about the neutral surface

Other terms have already been defined in the main body of this note.

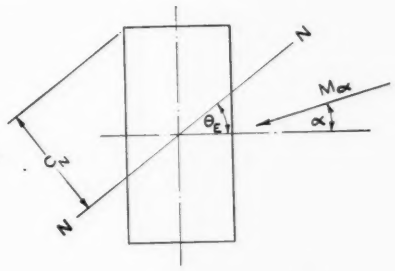

FIGURE 9.

For a maximum fibre stress f_5,

$$M_\alpha=\frac{I_N}{c_N}\,\frac{1}{\cos(\theta_E-\alpha)}\,[f_5+f_0(k-1)] \quad . \quad (12)$$

where

$$f_0=\frac{6f_2}{\varepsilon_5^2}\Phi_0-2f_5 \quad . \quad . \quad . \quad (13)$$

Expressions (2*b*), (12) and (13) enable a fairly rapid estimation to be made of the maximum permissible bending moment in a rectangular section beam in any material of the type represented by equation (1) when the plane of loading does not coincide with a principal axis.

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The Development of "Probe and Drogue" Refuelling

by

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1. Introduction

There have been many proposed, but few practical, methods of refuelling in flight since the first early experiments in 1923, and until some three years ago the only tried and accepted method was the "looped hose" system developed since 1934 by Flight Refuelling Limited, and still in use (with British equipment) by the United States Air Force.

This system consisted, briefly, in carrying a hose unit with a capacity of some 230 ft. of hose in the tanker aircraft, and a hauling line and windlass in the receiver aircraft. Operators were employed for both tanker and receiver aircraft.

To make contact between the aircraft, the receiver operator first trailed his hauling line, with a "sinker" weight on the end of it, so that the line curved downwards. The tanker aircraft then flew alongside and a projectile, attached to a "contact line," was fired from a line-throwing gun, so as to pass the contact line under the hauling line. The drag of the contact line then caused it to move rearwards, so that the two lines crossed, and the contact line dropped down until it became engaged in a "pawl grapnel" mounted on the top of the sinker weight.

Contact having been established, the sinker weight was then hauled up to the tanker operator, by means of a contact line winch. Next, the operator disconnected the sinker weight from the receiver's hauling line (a bayonet-type connector was used) and connected the hauling line to the nozzle on the end of the hose.

The tanker operator then released the hose drum brake progressively, and the receiver operator wound in his hauling line, connecting the hose from the tanker to the reception coupling in readiness for fuel transfer.

The advent of the turbo-jet engine, with its high fuel consumption rate made the air refuelling of single-seater fighters much more desirable than before and, in view of the complications of the "looped hose" method, set a number of problems.

After consideration of a number of highly improbable methods of refuelling a fighter, a scheme was prepared (*see* Fig. 1) using the looped hose principle. This consisted in carrying a small automatic windlass in the fighter, controlling some 50 ft. of hauling line at the extremity of which was attached the sinker portion of a "nozzle-sinker" device, and it was proposed that the tanker aircraft would trail a drogue on a contact line, which would fly substantially horizontally. The fighter pilot would select "Trail" on his windlass, and then fly his aircraft in such a manner as to cross the two trailing lines, thus achieving contact between the aircraft by the engagement of the contact line in a pawl grapnel integral with his sinker device.

The tanker operator would then reel in his contact line, and connect the "sinker" to the "nozzle" on the end of the hose. On a signal from the tanker, the fighter pilot would select "Wind in," thus connecting the hose to his reception coupling, where refuelling valves would automatically open, permitting fuel flow to begin.

On completion of the refuelling operation, the "nozzle-sinker" device would be separated by means of fuel pressure from the tanker, and the fighter pilot would be free to retract his windlass and go on his way.

This scheme had a number of disadvantages, chiefly

(*i*) The length of time taken to achieve contact and connect the hose across before fuel transfer could begin.

(*ii*) Fuel had to be transferred upwards, thus considerably increasing the pump horsepower required for a given rate of flow.

(*iii*) The necessity for co-ordination between the fighter pilot and the tanker operator, especially difficult under conditions of radio silence, or at night.

(*iv*) The weight and complication of the receiver equipment.

(*v*) The geometry of the hose, while in contact, made emergency disconnection by the fighter pilot difficult.

(*vi*) Only one fighter could be refuelled at a time; hence a section of four fighters would require four tankers.

To overcome these disadvantages, the "probe and drogue" method was conceived, before the modified looped hose method could be put into practice.

As is to be expected, the original conception of the probe and drogue method of refuelling was in a number of respects different from the method as used today. It is proposed first to outline the original conception and then to explain the stages of development resulting in the equipment in current use.

2. The Original Conception

2.1. THE TANKER

(a) Hose Unit

The tanker would carry a hose unit in each wing tip to accommodate about 30-40 ft. of 1½ in. bore hose. The hose units would be wound "catherine wheel" fashion, and lie flat in the wing tips. At the rearward end of each hose would be attached a reception

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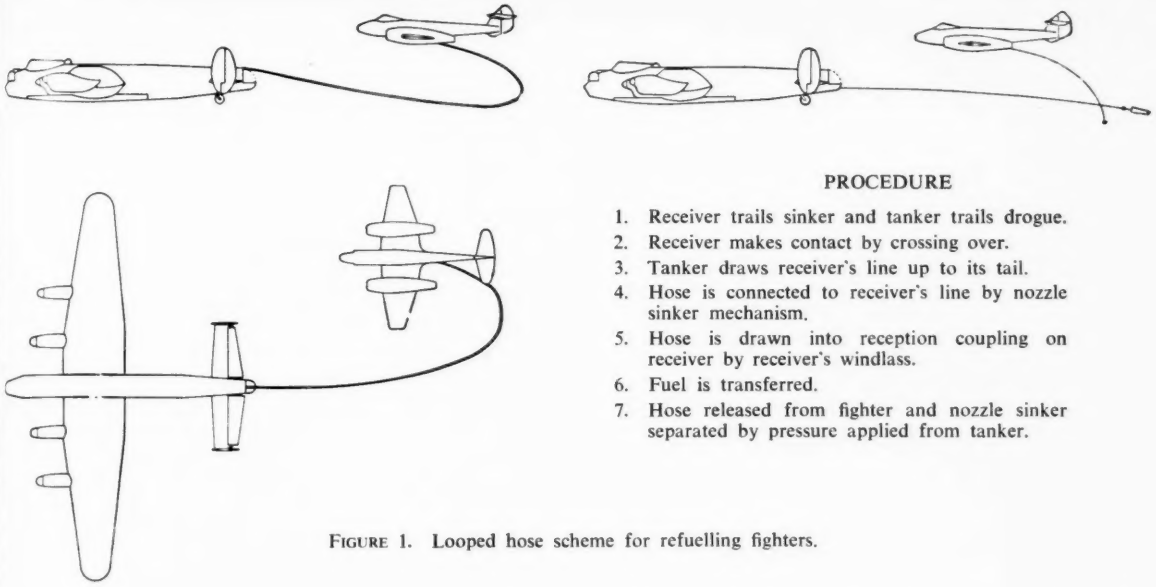


PROCEDURE

1. Receiver trails sinker and tanker trails drogue.
2. Receiver makes contact by crossing over.
3. Tanker draws receiver's line up to its tail.
4. Hose is connected to receiver's line by nozzle sinker mechanism.
5. Hose is drawn into reception coupling on receiver by receiver's windlass.
6. Fuel is transferred.
7. Hose released from fighter and nozzle sinker separated by pressure applied from tanker.

FIGURE 1. Looped hose scheme for refuelling fighters.

coupling, attached to a conical drogue, the reception coupling containing a spring-loaded non-return valve.

A constant torque in the "wind-in" direction would be applied to the hose drum, sufficient to overcome the drag and weight of the hose, but insufficient to wind in the hose, with the drogue drag applied. The hose drum would be as friction-free as possible, to obtain roughly the same torque in the "wind-in" direction, irrespective of the direction of motion of the hose.

A positive stop would come into operation when the pre-selected length of hose was trailed, to prevent further rotation of the drum.

(*b*) *Fuel control device*

A three-way cock would be fitted in the main fuel supply to the hose unit, automatically controlled, so that with the hose fully trailed it would be vented to atmosphere, the pump delivery line being stalled. On winding in some three feet of hose, the cock would operate and connect the pump supply to the hose, and close the vent. Associated with the fuel cock would be green and amber contact indicator lights, on the wing tip, which would face aft and be easily visible to the receiver pilot.

2.2. THE RECEIVER

The receiver would carry a probe on each wing tip, which in effect would be a rigid fuel pipe, extending forward, with a spring-loaded non-return valve in a nozzle formed on its extremity. The root end of the probe would connect with the refuelling galleries to the tanks. The non-return valve would be lightly spring-loaded, to prevent opening under air loads, but weak enough to open fully, before opening the valve in the drogue reception coupling (*see* Fig. 2).

The nozzle and coupling would form a fuel tight conduit when pressed firmly together, by virtue of a rubber seal in the coupling, the two non-return valves being mutually opened.

2.3. METHOD

(*a*) The hose unit would be fully trailed, the refuelling pumps running stalled, and the amber light illuminated.

(*b*) The receiver pilot would make contact, by flying his probe into the drogue, and continuing forward after engagement. By virtue of the shape of the drogue, the nozzle would find the centre of the coupling, the valves would mutually open, and the drag of the drogue would be transferred to the receiver's probe, thus forming a fuel-tight seal between the nozzle and the coupling.

(*c*) The hose tension being thus relieved of the drogue drag, it would allow the hose unit to start winding in, thus allowing the receiver to move backwards and forwards relative to the tanker within the limits of hose length, any tendency for slack hose being taken up by the hose unit.

(*d*) On the receiver flying forward three feet or more, the automatic fuel cock would operate and allow fuel to flow down the hose into the receiver's tanks, at the same time the green lamp would be illuminated and the amber light extinguished, to inform the pilot that fuel was now flowing.

(*e*) On completion of the refuelling, the receiver would simply fall back, thus reversing the automatic fuel cock, and finally disengaging when the hose drum stop came into operation. On disengagement, the nozzle and coupling fuel valves would spring shut, the hose valve first, to prevent fuel splash.

(*f*) To reel in the hose after the operation, the torque at the hose unit would be increased sufficiently to overcome the total hose tension.

This proposed scheme had a number of big advantages over the previous scheme, although a number of unknown factors caused some concern. These were:—

Advantages

(*i*) Receiver equipment was very simple and of small weight.

(*ii*) The tanker equipment, although fairly complex, was quite automatic.

(*iii*) The whole operation was under the control of the receiver pilot who, nevertheless, was called upon only to fly his aircraft in fairly loose formation.

(*iv*) Emergency breakaway could be effected at any time by the receiver.

(*v*) Two fighters could be refuelled simultaneously from one tanker.

Unknown factors

(*i*) The behaviour of the hose and drogue combination in free flight.

(*ii*) The effect of wing tip vortices from the tanker on the drogue and/or the fighter.

3. Development

The first investigation consisted in trailing a small parachute type drogue, known to be stable in itself, from the wing tip of a Lancaster aircraft, the length of trail being controlled by a manual winch.

In the main the drogue flew steadily, although it had a marked tendency to rotate about its own axis and would occasionally make small rotary movements about the trailing axis. This result seemed fairly promising, and a conical metal drogue of 120° included angle and 26 in. diameter was substituted for the parachute drogue.

Before this drogue had been trailed any distance the rotation about the drogue's axis caused the cable attachment to be twisted off, with consequent loss of the drogue. A 90° drogue of 26 in. diameter was substituted, the attachment being made through a small thrust bearing to prevent twisting the cable.

This drogue, on a short trail, flew very steadily but again rotated about its own axis. When the length of trailing cable was increased to 30 or 40 ft., however, the drogue began to rotate in a circle about the trailing axis, describing in effect an approximately 20° semi-angle cone, the apex being at the point of attachment on the wing tip. The pilot commented that he now felt a strong yawing tendency on the aircraft and, as the drogue seemed to be swinging rather close to the fin, it was trailed about 100 ft., with the idea that it might settle down to a more reasonable behaviour at this length. The drogue continued the circular motion, however, and as it seemed to be deflecting the wing tip rather excessively, and the load on the cable was too great for the manual winch to overcome, the drogue was jettisoned.

This concluded the initial wing-tip tests, the results being:—

(*a*) A conical drogue trailed from its apex was inherently stable.

(*b*) A drogue trailed from the wing tip was unsatisfactory owing to the circular motion imparted to it by the wing-tip vortex.

The next step was to trail a 90° conical drogue of 26 in. diameter from the tail turret position of a Lancaster on a short length of hose. This combination was inherently stable, at all speeds, the angle of trail being approximately 5° downward from horizontal.

By the courtesy of the Aeroplane and Armament Experimental Establishment, Boscombe Down, the possibility was investigated of contacting this drogue, with a probe on the nose or on the wing tip of a Meteor.

FIGURE 2(*a*). Mk. 1 Drogue Coupling.

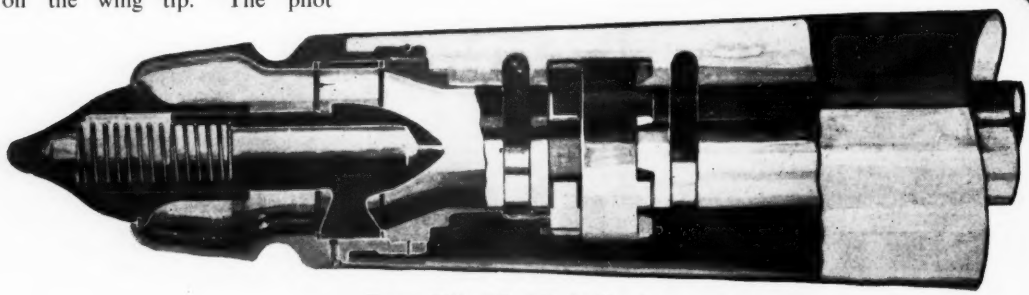


FIGURE 2(*b*). Mk. 1 Probe Nozzle.

It was reported that the drogue, as trailed, was in an area of disturbed air, which made formation by a Meteor difficult, but that a position some 10 ft. above or below, should give much better results. It was further reported that formation directly below or above the wing tip position was reasonable, but aft of the wing tip, the vortices made formation flying almost impossible. It appeared that in both the wing tip and tail positions it was desirable to keep the drogue below a line drawn roughly at 10° down from the horizontal, originating at the mainplane trailing edge.

This concluded the initial flight tests and the results were considered generally favourable. The proposed drogue was stable and if it could be trailed in an appropriate position relative to the tanker aircraft, contact as envisaged should not be difficult. The Meteor pilot had found that by use of dive brakes or flap he could maintain formation, with adequate fore-and-aft control at speeds down to 160 knots equivalent air speed.

4. The First Contact

In the light of the flight results, it was proposed to modify an existing hose unit in a Lancaster tanker, to give the constant torque feature and to trail approximately 65 ft. of standard 2·1 in. bore hose. It was estimated that this length and weight of hose, trailed from a position in the bomb bay, would place the drogue in the required undisturbed air position.

It was further proposed to fit a probe in the nose of a Meteor aircraft.

Flight Refuelling decided to push on with the project at top priority, and a Meteor 3 aircraft was hired from the Ministry of Supply. Within five weeks the first contact was made successfully, and a demonstration of the new technique was given to a visiting team of high ranking U.S.A.F. Officers.

The work done during this period consisted of:—

(*a*) The original tanker hose drum drive was by a hydraulic gear motor through chains to the drum. The original gear ratio was altered, and the base diameter of the drum packed up, to give a maximum hose speed of 10 ft./sec. This speed was considered adequate for the fastest contact, and gave a maximum hose tension at the drum, of the order of 250 lb. A large capacity adjustable pressure relief valve, in series with a shut-off valve, was placed across the supply lines to the motor so that, by adjustment of the pressure relief valve, the motor torque could be varied, or for winding-in purposes, full power could be obtained by closing the shut-off valve.

A " goal post " structure was attached to the underside of the aircraft (Fig. 3) to guide the hose onto the drum, to serve as a stowage for the drogue when wound in, and to carry the green and amber contact lights.

A cam nut on a small screw jack attached to the hose drum spindle, served to operate micro-switches, (*i*) to bring in pawl stops at the full trail position, (*ii*) to operate the contact lights (no fuel cock was fitted at this stage).

The pawl stops consisted of spring-loaded pawls, which engaged with notches in the drum flanges, the engagement being manual on the original unit. The manual engagement was deleted in favour of an actuator, energised through the appropriate micro-switch.

(*b*) A drogue, reception coupling, and nozzle were designed (*see* Fig. 2). The reception coupling valve spring gave a load of approximately 8 lb. and the nozzle valve spring approximately 5 lb. In view of the high friction value of the existing hose unit, spring-loaded toggles were provided in the reception coupling, to engage in an annular groove on the nozzle, and designed to give an engaging load of approximately 5 lb. with a " pull off " load of 180 lb.

(*c*) A fabricated probe structure was built on the Meteor front bulkhead and nose-wheel structure, to carry a 39 in. probe which protruded from the centre of the nose fairing. This length of probe enabled the

FIGURE 3. Meteor 3 and tanker over Poole Harbour. *Charles E. Brown*

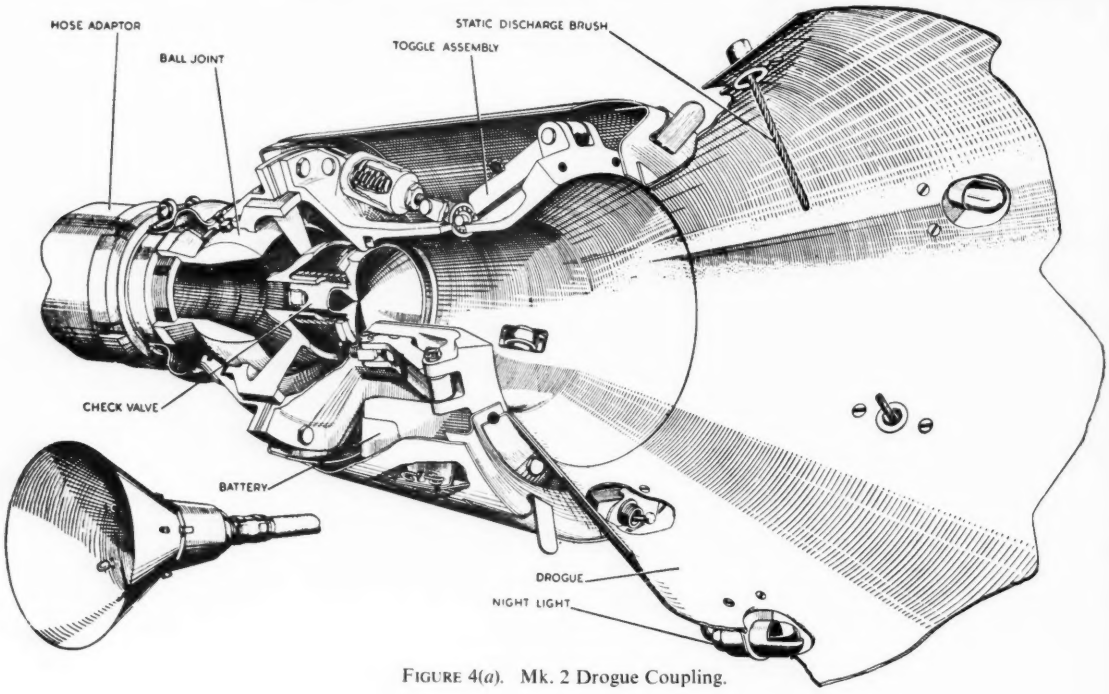


FIGURE 4(*a*). Mk. 2 Drogue Coupling.

pilot to see the nozzle from the cockpit in comfort. A manual probe-release system was incorporated to enable the pilot to jettison the probe, should he for any reason be unable to disconnect in the normal manner after making contact. Fortunately, this device was never needed in practice.

(*d*) While modification work was in progress, the pilot, Mr. P. R. Hornidge, familiarised himself with the Meteor, not having flown this type before.

Contact was established at the first attempt, and it was soon realised that, given reasonably calm air conditions, the average pilot could become proficient with very little practice. Intensive flying continued, and a number of minor snags were corrected.

Because of the friction of the hose drum and its drive, it was found that with a low torque setting on the drum, violent hose whipping occurred with a fast contact. This resulted in excessive stresses in the probe structure, which had to be strengthened to meet this hazard. If the torque setting was increased to prevent hose whipping, the fighter tended to break away from the reception coupling prematurely on falling back and to prevent this the break away load on the toggles was increased to 300 lb.

There was some tendency for the probe to "hang up" on the 90° included angle drogue, and this was modified to 60°, which effectively cured this tendency.

5. Passing Fuel

The next stage in development was to fit a fuel receiving system into the Meteor and a pumping system with the automatic fuel valve in the tanker.

Before trying to pass fuel, however, it was necessary to check that the nozzle reception-coupling combination

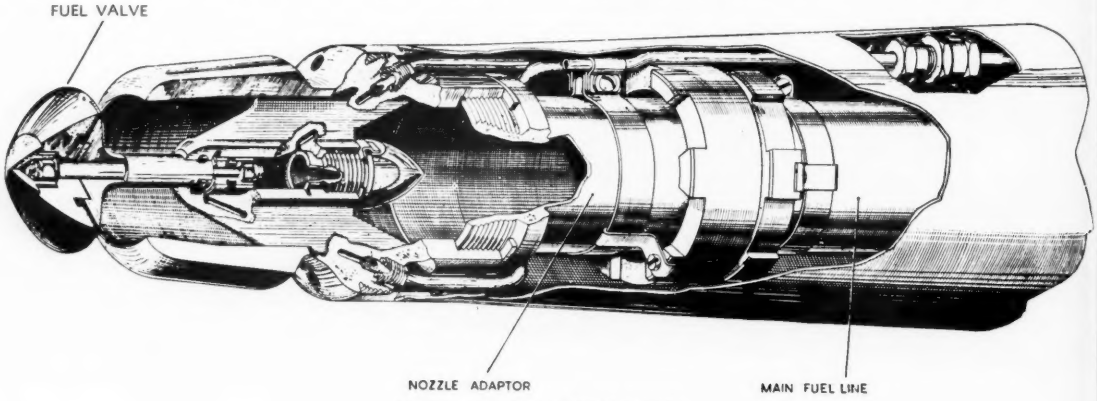


FIGURE 4(*b*). Mk. 2 Probe Nozzle.

was effective in flight. To do this a small water tank was connected to the hose unit and the hose primed with water. The fuel connection of the nozzle was blanked off.

Insufficient allowance had been made for the contraction of the hose when tension was released, with the result that the flight test observer stationed by the water tank received an involuntary shower bath! The nozzle combination was quite watertight while in contact, but there was a splash on initial contact and breakaway, particularly if these operations were done rather slowly. This splash could not be accepted because, apart from the fire risk involved, which was probably small, the fuel would obscure the windscreen, causing grave inconvenience to the pilot.

To overcome the splash difficulty, the rather retrograde step was taken of fitting a pilot-controlled nozzle, the nozzle valve being extended or retracted by means of a small hydraulic cylinder within the nozzle, controlled by an electric trigger switch on the control column, through an electro-hydraulic selector valve. With this arrangement contact was made with the nozzle and coupling valves shut, and the pilot opened these valves after making contact and flying forward to open the tanker main fuel valve (*see* Fig. 4).

The Meteor fuel system consisted of a Flight Refuelling Mk. 11 fuel filling valve in each main tank, connected through 2¼ in. diameter D.T.D. 310 pipes, fitted with F. R. pipe conectors, to the nozzle. An oversize vent system was provided to cater for possible malfunctioning of either of the filling valves.

The tanker pumping system comprised a set of five S.P.E. booster pumps, giving a combined delivery of approximately 100 gallons/min. The automatic fuel valve consisted of a one-inch Saunders valve for venting and a two-inch Saunders valve for the main fuel run, both operated by a Rotax linear actuator.

6. The 12-Hour Flight

No difficulties were experienced with the passage of fuel with the arrangement just described, and it was decided to carry out a 12-hour endurance flight, to obtain experience with the equipment and to publicise its possibilities.

The Meteor was equipped with certain extra comforts for the pilot, such as a tray for chocolate and so on in place of the reflector gun sight, stowages for thermos flasks of coffee and a sandwich container, an upholstered seat, and a relief tube.

The flight was scheduled for Sunday 7th August 1949 and the Meteor took off with Mr. P. R. Hornidge at the controls at 5.20 a.m. and landed at 5.23 p.m., having completed 10 air refuellings involving 3,000 gallons of kerosine. No snags occurred throughout the day, and it is noteworthy that during the last hour cloud was 8/8ths and visibility half a mile. To bring the Meteor into the circuit the pilot remained in contact with the tanker, which was equipped with Rebecca. The tanker refuelled on the ground three times, to carry the necessary cargo of fuel for the Meteor.

In parallel with the Meteor development, experiments had been made with a Lancaster receiver, the drogue being increased in diameter to 32 in. The experiments showed that the technique was practicable for the larger aircraft, and the 32 in. diameter drogue was made standard for fighters and large aircraft.

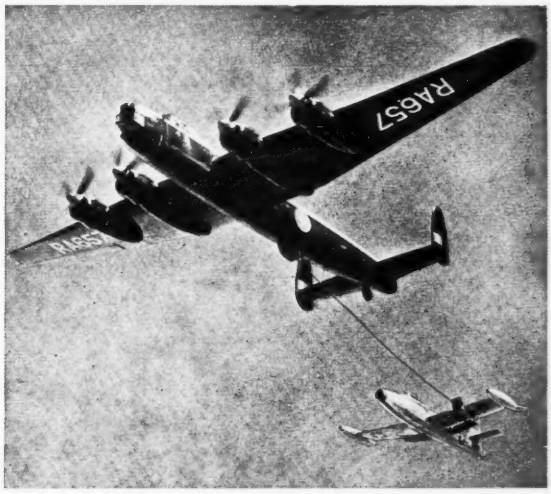


FIGURE 5. Lincoln and F.84 in contact.

7. F. 84s Across the Atlantic

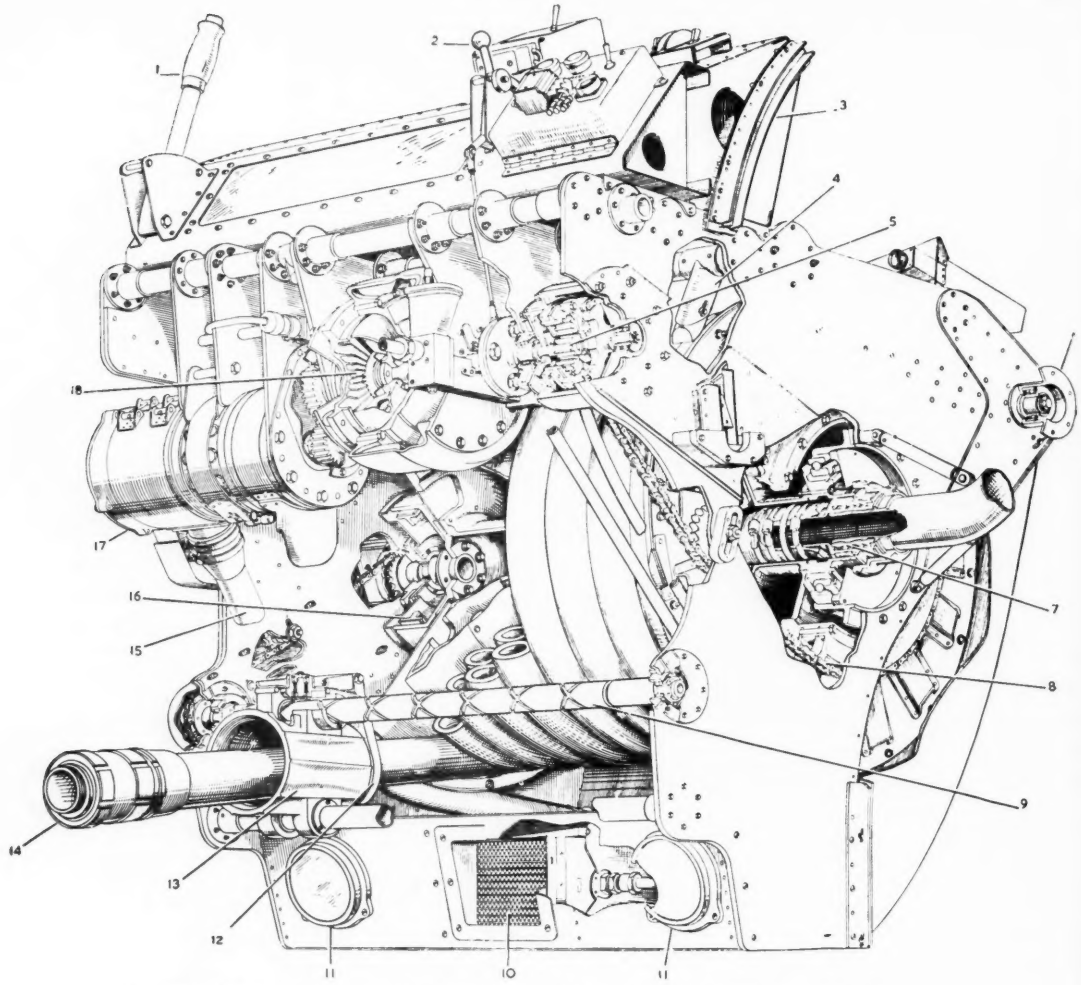
Success of the probe and drogue method of air refuelling was now established, and contracts were placed with Flight Refuelling for modification of a Mk.4 Meteor and a Lincoln tanker for the R.A.F., and a B.29 tanker, two F.84 receivers and a B.29 receiver for the U.S.A.F. The U.S.A.F. contract resulted in the operation "Fox-Able-Four" on 22nd September 1950, in which the two F.84's flew from Manston, across the Atlantic non stop, being refuelled in turn by a Flight Refuelling Lancaster tanker near Prestwick, the Lincoln near Iceland and the B.29 near Newfoundland. One of the F.84s failed to refuel at Newfoundland, having damaged its nozzle valve while breaking contact on the previous refuelling. The pilot unfortunately had to bale out and the aircraft was lost, as unexpectedly high headwinds prevented him from reaching an alternate airfield.

8. The Mark 7 Hose Unit

The new tankers were fitted with a new hose unit, designated the Mark 7. This unit (*see* Fig. 6), designed to trail 65 ft. of hose and to have minimum friction, consisted essentially of a 5 h.p. continuously rated electric motor driving a Vulcan Sinclair Fluidrive through a reduction gear, which in turn drove the hose drum through a 4:1 epicyclic gear box and a chain.

Driven from the centre of the drum through another chain was a serving gear shaft, on which a double helical groove was cut. A follower located in the groove caused a hose fairlead to travel from side to side, effectively ensuring an even lay of the hose on the drum.

The original type of micro-switch arrangement was retained, with a similar pawl-stop shaft. A small



1. Brake lever.
2. Scoop control lever.
3. Radiused runner.
4. Pawl stop.
5. Epicyclic gear.
6. Mounting bracket.
7. Revolving fuel gland.
8. Main driving chain.
9. Serving gear shaft.
10. Oil cooler.
11. Warning lights.
12. Arrester plate.
13. Serving gear guide.
14. Hose adaptor.
15. Blast cooling inlet duct.
16. Brake.
17. Drive motor.
18. Fluid drive coupling.

FIGURE 6. Mk. 7 hose drum unit.

friction brake was incorporated for trailing and parking purposes.

Additional safety features included an automatic mechanical device for engaging the pawl-stops in the event of electrical failure, and a "slug" on the hose which positively prevented the hose from leaving the aircraft, by coming up against the hose fairlead, in the event of pawl stop failure.

A number of snags were experienced with this unit during early flight tests, and were corrected as follows:—

(*i*) The electric motor r.p.m. were found to be down on expected performance. As the torque transmitting capacity of the Fluidrive varies as the square of the r.p.m. this resulted in an inadequate hose tension, until the primary drive ratio had been altered.

(*ii*) The follower on the serving gear shaft, although theoretically adequate, repeatedly fractured as a result of dust and grit accumulating on the shaft. Experiments were made to obtain a stronger follower, by mounting the shaft between the centres of a lathe and attaching the follower to the saddle, the lead screw being disconnected. Eventually a follower was developed which would move the saddle backwards and forwards, with the lathe turning at full speed, in spite of all attempts to stop it by pushing swarf, dust and stones etc. into the follower.

(*iii*) The pawl-stop assembly, which had previously given no trouble on the original hose unit was now subjected to more severe shock loads, as a result of the smaller drum flange radius. The various parts were progressively strengthened, and the material of the

stops was improved, and finally satisfactory results were achieved on the later Mk. 11 and Mk. 12 units by improving the lead in to the notches on the flanges. A snag which proved more difficult to trace then developed. From time to time, for no apparent reason, the pawl-stop actuator would be broken, usually on a fairly violent breakaway. This proved to be caused by the pawls engaging while the actuator was still extending and tending to make the actuator extend more quickly than its design permitted. A spring shock absorber fitted in the actuator arm eventually cured this trouble.

(*iv*) Very erratic operation of the pawl stops and main fuel cock were at first experienced. The side plates of the Mk. 7 unit had been fabricated from ¼ in. Alclad to speed production, and the micro-switches had been supported on the side plates, whereas the cam-nut was supported from the drum. Under load, the deflection of the side plates was sufficient to alter the micro-switch settings by as much as 10 ft. in terms of hose length. This snag was effectively overcome by mounting the switches and cam-nut as a self-contained unit, drive from the hose drum spindle being through a small universal joint.

The hose unit was mounted in place of the radar scanner on the Lincoln, the hole being enlarged to accept the unit. In the B.29, the unit was made retractable, and extended through an enlarged hole in way of the dorsal turret. The fuel pumps fitted in both aircraft were Flight Refuelling Limited Mk. 4 centrifugal pumps, giving an effective rate of flow of 230 gallons/min. The pump fitted in the B.29 was electrically-driven, and the Lincoln pump was hydraulically-driven.

9. The Receivers

(*a*) *The Mk. 4 Meteor* was similar to the previous Mk. 3 installation.

(*b*) *The B.29* was already equipped with F.R. Mk. 7 filling valves in the inboard wing and bomb-bay tanks, and it was necessary merely to provide probe structure and lead fuel pipes back from the probe to the tanks. In addition, an F.R. ground pressure refuelling coupling was provided, feeding into the flight refuelling lines. A scavenge system was fitted, comprising a combination of F.R. float switch and S.P.E. pump in a small container, which effectively transferred back into the bomb-bay tank the 30 gallons of fuel remaining in the refuelling lines after an operation.

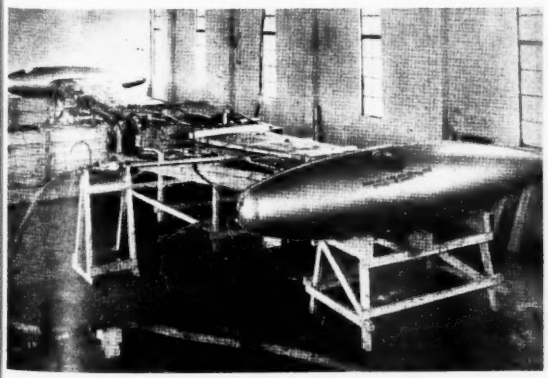


FIGURE 7. F.84 fuel system test rig.

Possible malfunctioning of any of the filling valves was catered for by secondary electrical shut-off valves in the feeds to the tanks, each controlled by its own float switch.

A little trouble was experienced with the nozzle valve on this aircraft because in the absence of a hydraulic supply, it was necessary to use the 1500 lb./in.² pneumatic system for the bomb doors. The nozzle seals, which gave no trouble with hydraulic leakage, were inadequate for air pressure and had to be replaced by cup type seals in a redesigned piston.

(*c*) *The F.84* system was much more complicated. Because of the nose air intake for the engine, it was considered necessary to mount the probe in the port wing leading edge, at approximately half the semi-span. This gave an unsymmetrical filling point and, in view of the number and diversity of tanks to be filled, it was essential to fill them all in the same length of time, to obtain maximum overall rate of flow.

To achieve this, pressure loss calculations were made, equating the losses to each individual tank, and a full-scale test rig was then constructed, to check the calculations (*see* Fig. 7). The pipe runs were a fantastic shape, to avoid existing equipment, and in many places the shops had to call in the assistance of two draughtsmen, with very long thin arms, to assist in the installation on the aircraft. As these two draughtsmen were largely responsible for the pipe run anyway, it was a case of poetic justice!

So limited was space within the leading edge of the wing tips, that the tip tank shut-off valves were separated from their actuators, by means of Teleflex runs approximately 4 ft. long. The tip tanks were fed by lines tapped into the normal tip tank transfer lines, with shut-off valves controlled by float switches within the tip tanks. The air pressure leads to the tanks were increased to one-inch diameter and vented overboard through an electrically-actuated three-way valve, which also provided the extra venting required by the wing tanks. In addition, F.R. tank pressure relief valves were fitted to the tip tanks, designed to "crack" at 7½ lb./in.² and to give immediately a full bore flow of 65 gallons/min. at this pressure (*see* Fig. 8).

Shut off was provided in the wing and fuselage tanks by F.R. Mk. 12 filling valves, supplemented for the fuselage tank by an electrically-actuated valve, as no extra venting could safely be devised for this particular tank.

A small indicator was fitted on the instrument panel, to show when each tank had filled. Starting with empty tanks, all tanks shut off within 30 seconds of each other.

The only troubles experienced with these aircraft were initial teething troubles with the float switches. The maximum size hole available in the bag tanks was two-inch diameter and, as no proprietary switch of this size was available, it was necessary to design one for the job. The early switches worked perfectly in the laboratory, but were susceptible to mishandling, and in the confined spaces into which they had to be fitted some mishandling was almost inevitable. However, a

reliable and robust switch has now been developed, which fits in this restricted space.

On all aircraft the piping was in D.T.D. 310 joined with F.R. pipe connectors.

10. Flight Tests

Flight tests brought a recurrence of premature breakaway troubles. Although the unit was vastly superior to the original one in terms of friction and general response to receiver movement, the use of the larger pump, with high stall pressure, and high flick pressures on closing the increased rate of flow, caused an added breakaway load on the reception coupling toggles. To overcome this tendency the pull-off load was increased to 600 lb. and finally to 800 lb. before the trouble was finally cured.

Some increased difficulty in making contact with the wing probe was experienced, and pilots needed rather more practice with this type of probe than with the nose probe before becoming proficient. This resulted in some failures due to bent nozzle valve stems caused by pilots flying well out of position and causing premature breakaways with the valves open.

11. Three at Once

The next stage in development was to modify a tanker to refuel three fighters simultaneously, and also capable of refuelling a larger aircraft at considerably higher rates of flow from the hose unit in the fuselage.

To overcome the wing tip vortex problems mentioned previously, the hose units were underslung so that the hose fairlead was approximately 3 ft. below the lower surface of the wing. This, in conjunction with a 65 ft. trailed length of hose, enabled the fighters to stay below the vortex. Before work on the nacelles began the position was checked by trailing a dummy drogue on a short length of hose fastened to a pylon below the wing tip.

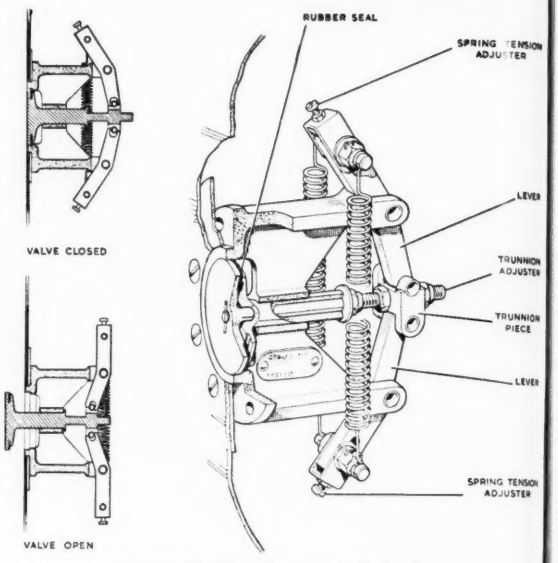


FIGURE 8. Tank pressure relief valve.

Two new hose units were developed for this purpose. The Mk. 9 unit, carrying a larger hose and being correspondingly more powerful, was retractably mounted in

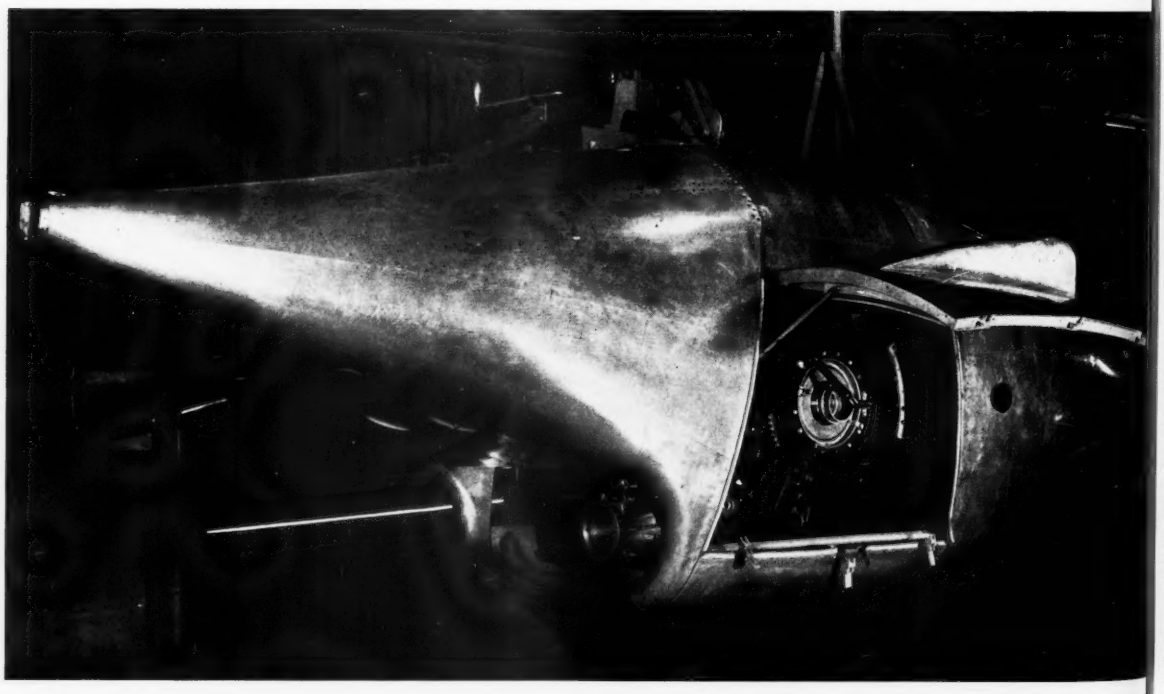


FIGURE 9. Wing-tip nacelle and Mk. 2 hose unit.

the fuselage. The drive was similar in principle to the Mk. 7 unit, except that a two-speed epicyclic gear box was provided, to obviate the necessity for slowing down the aircraft to reel in the hose after the operation. The pawl stops were replaced by a friction clutch device, which brought the unit to rest more gently at full trail, because of the greater mass that had to be arrested.

The wing tip nacelles contained Mk. 11 units, which were basically Mk. 7 but included a two-speed epicyclic gear box instead of the original 4:1 gear. In addition, electrical operation of the parking brake was incorporated and the circuit was redesigned to provide automatic remote control. Cast side plates were fitted in place of the Alclad plates of the Mk. 7 (*see* Fig. 9).

The nacelles were designed with frontal air intakes to (*a*) reduce the drag of the nacelle, (*b*) provide an air flow over the drogue, when in the stowed position, to assist initial trailing by a reduction of the depression behind the "step" in the bottom surface. On flight test, the pilot reported that the modifications had not noticeably affected the performance or handling of the aircraft, though there was a small yawing tendency when a fighter broke away from one of the wing tip units. If anything, the addition of the nacelles had tended to delay the stall by improving velocity distribution over the outer wing. Fortunately the stall characteristics of the aircraft as a whole were not affected.

Some trouble was experienced at altitude because of over-cooling of the Fluidrive oil in the wing tip units. The Fluidrives have adjustable oil circulation, by which the output torque can be varied. This control had been manually operated on the Mk. 7 unit, to enable full torque to be applied for winding in, but on the Mk. 11 unit, it was set to give the required operational torque, wind-in torque being provided through the two-speed gear-box. In consequence, a reduced oil circulation was available, and the cooler tended to over-cool, with resultant loss of torque. This snag has been overcome by fitting the coolers with thermostatically controlled shutters, which close off the air flow through the cooler until an oil temperature of at least 40°C. is reached.

12. Higher Speeds and Higher Rates of Flow

The Mk. 9 hose unit fitted to the three-point-tanker was capable of trailing 100 ft. of 2½ in. bore hose, and had sufficient power for operation at air speeds up to 250 m.p.h. equivalent air speed. The next step in development was the production of the Mk. 14 hose unit, in both D.C. and A.C. forms, capable of trailing 100 ft. of 3 in. bore hose at air speeds up to 300 m.p.h.

The Mk. 14 hose unit was based on the original Mk. 9 design, but included a number of detail refinements, in the interests of best utilisation of the power available, for the higher air speed. An overall mechanical efficiency of 84 per cent. was finally achieved.

A 10 h.p. electric motor rotated the Fluidrive, through a Duplex chain primary drive, enclosed in an oil-bath, and fitted with a spring-loaded jockey sprocket. The Fluidrive output shaft connected with a two-speed gearbox of improved design, which then turned the final chain drive, as in the Mk. 9 unit. The Mk. 9 type of primary brake was incorporated, together with an additional emergency brake which, though lighter than the Mk. 9 type, was considerably more effective. The serving gear was of the Mk. 7 type and was driven by chain, directly from the drum. A Flexibox carbon-face type of rotating seal was fitted at the fuel entry to the drum, and resulted in a considerable saving in friction at this point. In view of the wide range of air speed over which the unit could operate, a control switch and actuator were provided for Fluidrive torque adjustment, enabling the tanker operator to adjust the current consumption of the unit to suit the air speed of operation. With a view to high altitude operation, the complete unit was enclosed in a casing, capable of being supplied with warm air, to maintain the gearboxes, bearings etc. at a reasonable working temperature.

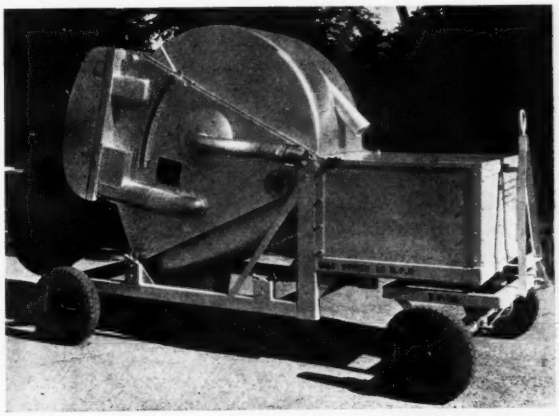


FIGURE 10. Mk. 14 hose unit on universal hose unit trolley.

13. The Future

Development continues, with the object of refuelling at still higher air speeds and greater rates of flow. The equipment developed is only limited in use by the performance of aircraft at present in service, although new aircraft with better performance and demands for greater quantities of fuel in less time will require the new equipment now in the design stage.

The new aircraft will, by requirement, incorporate ground pressure refuelling and only minor modification should then be necessary to fit a probe and tap into the pressure refuelling gallery, as the fuel system requirements for the two functions are basically identical.

It is not beyond the bounds of reason that really large tanker aircraft may be equipped as four-point tankers, capable of flight refuelling a complete section of fighters in less than two minutes.

ACKOWLEDGMENTS

The author acknowledges the permission of Flight Refuelling Ltd. to publish this account, and also the help and advice given in its preparation by the technical staff of the Company.

The 1953 Garden Party

APPROPRIATELY for Coronation Year and the year in which the 50th Anniversary of the first powered controlled flight will be celebrated, the Society's fourteenth Garden Party on 14th June 1953 was—by all accounts—one of its most successful.

Through the courtesy of the de Havilland Aircraft Co. Ltd., this year's Garden Party was held at Astwick Manor, Hatfield, the home of the de Havilland Aeronautical Technical School. The lawns, the trees, the stream with its little bridges which separated the tea marquees from the rest of the grounds, the flowers which had been planted over-night, and the whole setting were ideal for a Garden Party. The weather was far from ideal; loyally, it was typical Coronation Summer weather, but in spite of it some 4,500 members and guests were present. The many distinguished guests from this country and overseas included a number of delegates from the International Civil Aviation Organisation Assembly meeting at Brighton. The many family groups of members indicated that the introduction this year of tickets at half price for children under 15 was a good idea.

The layout of the grounds of Astwick Manor (on the far side of Hatfield Aerodrome) enabled the aircraft to be lined up, between the marquees and the car park, on each side of a wide grass avenue leading to the aerodrome proper; this created a much more intimate area for inspection, discussion, and perambulation, and later for the flying, while the runways of Hatfield Aerodrome permitted more modern types of aeroplanes to take part in the flying programme.

To mark the fiftieth anniversary of powered controlled flight, special efforts had been made to obtain representative types of early and modern aircraft and although some of the aeroplanes had been seen at previous Garden Parties, with the co-operation of the Science Museum, the Royal Air Force, the Royal Auxiliary Air Force and the Admiralty, the Air Ministry and the Ministry of Supply, and the United States Navy, there was a variety of aircraft, including some representative of the 1939-45 War and some post-war types. The United States Air Force were to have been represented in the flying programme by two Republic Thunderjets and two North American Sabres but unfortunately, because of the local meteorological reports, their appearance was cancelled shortly before flying began.

Flight

The President, Sir William Farren, C.B., M.B.E., F.R.S., F.R.Ae.S., and Miss Farren, received members and their guests —in this case the Paramount Chief of the Ashanti.

Their place in the flying programme was taken by an Elizabethan of British European Airways which, open for inspection in the aircraft park before the flying display, caused much interest and a long queue of admiring visitors.

The arrival of six Gloster Meteors of No. 604 County of Middlesex Fighter Squadron, Royal Auxiliary Air Force, coincided with one of the worst bouts of weather which did not prevent them from being punctual to the minute and giving an excellent performance.

An unexpected visitor towards the end of the flying programme was the Handley Page Victor which "took in" Hatfield on a circuit from Radlett.

A small static display in a marquee housed the first British jet-propelled aeroplane, the Gloster/Whittle E.28/39, a radio-controlled model glider which was demonstrated at the 1952 Garden Party and which has since been fitted with a slow-burning rocket, and a number of aero-engines, which included a 60 h.p. Green engine used by Colonel S. F. Cody in 1910-12, a Napier Lion (1918), a Rolls-Royce Eagle (1915) and "R" of Schneider Trophy fame in 1929 and 1931, a Bristol Jupiter (the first engine to be produced by the Bristol Company) of 1921, the first type of engine to be built by de Havilland's, a Gipsy I of 1927, as well as more modern types, and some excellent cloud photographs lent by British Overseas Airways Corporation.

The "souvenir" printed programme recorded in scrap-book form some of the aeronautical events from 1903 to 1953.

By kind permission of the Air Council, the Central Band of the Royal Air Force, conducted by Flight Lieutenant F. A. Gale, Director of Music, R.A.F., played during the afternoon.

The Blackburn Monoplane of 1912.

Charles E. Brown

10 THE ILLUSTRATED SPORTING AND DRAMATIC NEWS. JULY 4, 1903.
KITE FLYING COMPETITIONS BY THE ROYAL AERONAUTICAL SOCIETY NEAR WORTHING.
Mr. S. H. R. Salmon's "Box" kite.
Mr. S. F. Cody and his black kite.
(The kites were to attain a minimum altitude of 3,000 feet, and be afloat at least an hour.)
Major Baden-Powell getting ready one of his kites.
Mr. S. F. Cody's black kite ready for the signal.

The Society's first Garden Party, perhaps—part of the page for 1903 from the 1953 " Aviation Scrap Book " programme.

An informative and lively description of the aircraft and of the events of the afternoon was broadcast by Mr. B. J. Hurren of the Fairey Aviation Co. Ltd.

The President and Council of the Society wish to express their sincere appreciation to the de Havilland Aircraft Co. Ltd, and the Ministry of Supply, for making Hatfield Aerodrome and Astwick Manor available for the Garden Party.

The Council is particularly indebted to Sir Geoffrey de Havilland, and to the Directors and Staff of the de Havilland Aircraft Co. Ltd., and to the Students and Staff of the Technical School for their generous and practical help, not only on the day of the Garden Party, but during the weeks of preparation and organisation. Mr. C. A. Pike, Aerodrome Manager at Hatfield, was in charge of flying and Mr. T. C. Grewar of aerodrome arrangements and to them and their assistants the Council pays special tribute for their whole-hearted help and enthusiasm.

Much of the success of the Garden Party depends on the pilots and ground crews and the Council appreciates greatly the work of all those who took part in the flying events and who brought aircraft for the aircraft park.

The Council thanks particularly the Admiralty, the Air Ministry, the Ministry of Supply, the Ministry of Civil Aviation, The Royal Air Force, the Royal Auxiliary Air Force, the United States Navy and Air Force, and the British Aviation Insurance Co. Ltd., for their help and co-operation.

The Council is greatly indebted to the many private owners and to the following for making the aircraft and static exhibits available:—The Air Ministry; the Admiralty; the Aeroplane and Armament Experi-

The Deperdussin of 1910.

mental Establishment, Boscombe Down; Blackburn and General Aircraft Ltd.; Bristol Aeroplane Co. Ltd.; British European Airways Corporation; de Havilland Aircraft Co. Ltd. and de Havilland Engine Co. Ltd.; Fairey Aviation Co. Ltd.; Flightways Ltd.; Hampshire Aeroplane Club; Hawker Aircraft Ltd.; London Gliding Club; the Low Speed Aerodynamics Research Association and the firms who have assisted them; the Ministry of Supply; D. Napier and Son Ltd.; the R. G. J. Nash Collection of Mechanical Transport; Percival Aircraft Ltd.; A. V. Roe and Co. Ltd.; Rolls-Royce Ltd.; the Royal Aircraft Establishment; the Royal Air Force; the Royal Auxiliary Air Force; the Royal Swedish Air Force; the Science Museum, South Kensington; Shell Mex and B.P. Ltd.; Short Brothers and Harland Ltd.; the Shuttleworth Collection; the United States Navy; and the Vintage Aeroplane Club.

Dr. I. F. Bishop was in attendance as Honorary Medical Officer during the afternoon and the Council thanks him for his services.

The efficiency of the Royal Automobile Club, the Hertfordshire Constabulary and the British Legion Car Attendants in traffic and car parking arrangements was much appreciated and the Council also thanks the R.A.F. Apprentices from Halton and the St. John Ambulance and Nursing Brigade for their services and help.

The co-operation of the Pyrene Co. Ltd. in arranging extra fire fighting equipment, the Antone Co. Ltd. for providing the loudspeaker arrangements, and Gilbert-Ash Ltd., is gratefully acknowledged.

The success of the Society's Garden Parties depends largely on the friendly help and co-operation of the Aircraft Industry and organisations concerned with aviation in Great Britain, not only those individuals, firms and organisations named in these acknowledgments, but many others in minor ways; their help involves extra work and trouble which is unstintingly given and to them all the Council and Staff of the Society are sincerely grateful.

Charles E. Brown

The Bell 47D and Westland S.51 helicopters formating.

The following puts on record the aircraft which took part in the Flying Programme, those which were shown on the ground and the engines and other items shown in the Static Exhibit:

FLYING PROGRAMME

	Aircraft	*Owner*	*Pilot*
1.	Hawker Hart Hawker Hurricane Hawker Tomtit	Hawker Aircraft Ltd.	A. W. Bedford Frank Bullen Neville Duke
2.	Bristol Fighter Sopwith Pup	Shuttleworth Collection	Air Cdre. A. H. Wheeler W/Cdr. R. F. Martin
3.	Gloster Gladiator	V. H. Bellamy	V. H. Bellamy
4.	D.H. Cirrus Moth	de Havilland Aircraft Co. Ltd.	P. Fillingham
	Hawker Cygnet	Hawker Aircraft Ltd.	Frank Murphy
	Blackburn B.2 Trainer	Blackburn and General Aircraft Ltd.	B. Watson

Flight

Looking towards the car park with the Static Exhibit and the "Ibis" on the left.

Flight

Part of the Aircraft Park, showing the Gloster Gladiator, the Sopwith Pup and the Bristol Fighter.

	Aircraft	*Owner*	*Pilot*
5.	Gliders:		
	Slingsby Sky	London Gliding Club	G. H. Lee
	D.F.S. Meise	The Admiralty	Lt. Cdr. G. A. J. Goodhart
6.	C.30 Autogiro	H. J. Barnes	Norman Hill
7.	Fairey Fulmar	Fairey Aviation Co. Ltd.	D. J. Masters
8.	Percival Gull Six (Jean Batten's)	Percival Aircraft Ltd.	B. Radley
9.	D.H. Beaver	de Havilland Aircraft Co. Ltd.	R. L. C. Blyth
10.	Helicopters:		
	Westland S.51	The Ministry of Supply	Lieut. Morton
	Bell 47B-3	British European Airways	First Officer Crewdson
11.	Miles Hawk Speed Six	R. R. Paine	R. R. Paine
12.	D.H. Mosquito B.35	de Havilland Propellers Ltd.	Sqdn. Ldr. D. de Villiers
13.	Gloster Meteors (six)	Air Ministry	No. 604 County of Middlesex Fighter Squadron, R.Aux.A.F.
14.	Supermarine Spitfire Vickers Wellington	Air Ministry	Flg. Officer T. Glover Flt. Lieut. W. N. Trimble
15.	English Electric Canberra	Ministry of Supply	Sqdn. Ldr. E. H. Turner
16.	Airspeed Ambassador (Elizabethan)	British European Airways	Capt. W. Baillie
17.	Blackburn Monoplane 18. Deperdussin	Shuttleworth Collection	Sqdn. Ldr. G. Banner Wing Cdr. C. G. B. McClure
19.	Avro 707B	Ministry of Supply	Sqdn. Ldr. H. T. Murley

IN THE AIRCRAFT PARK

Aircraft	*Owner*
Avro 504 K	R. G. J. Nash Collection of Mechanical Transport
Avro Lincoln Avro York	Ministry of Supply
B.A.C. Super Drone	John E. Fricker
Beechcraft Expeditor	U.S. Navy
Bristol Bulldog	The Science Museum
Airspeed Consul de Havilland Leopard Moth de Havilland Tiger Moth	de Havilland Aircraft Co. Ltd.
de Havilland Hornet Moth	John Cooper
Douglas Super-Dakota DC-3	U.S. Navy
Fairey Firefly VI Fairey Junior	Fairey Aviation Co. Ltd.
G.A.L. Cygnet	T. F. W. Gunton
Gloster Meteor N.F.11	Air Ministry
Bert Hinkler's Ibis	H. Stisted
Percival Proctor I	Shell Mex and B.P. Ltd.
Percival Proctor V	Percival Aircraft Ltd.
S.A.A.B. Safir	Royal Swedish Air Force
Short Sealand	Short Bros. and Harland Ltd.

STATIC DISPLAY

Exhibit	*Owner*
Gloster/Whittle E.28/39	The Science Museum
Radio-Controlled Model Glider	Low-Speed Aerodynamics Research Association
Hucks Starter	The Shuttleworth Collection
Display of Cloud and Comet Photographs lent by British Overseas Airways	

AERO-ENGINES

Engine	*Owner*
Bristol Jupiter Bristol Hercules Bristol Coupled Proteus	Bristol Aeroplane Co. Ltd.
130 h.p. Clerget	The Shuttleworth Collection
D.H. Gipsy I D.H. Goblin II	de Havilland Engine Co. Ltd.
60 h.p. Green Engine	S. F. L. Cody
80 and 110 h.p. Le Rhone	The Shuttleworth Collection
Napier Lion Napier Sabre VII	D. Napier and Son Ltd.
Rolls-Royce Eagle Rolls-Royce "R"	Rolls-Royce Ltd.

The Aeroplane

A Hawker formation of mixed vintage—the Hart, Hurricane and Tomtit—began the flying programme when the weather was, perhaps, at its worst.

The Aeroplane

The Avro 707, Great Britain's first delta aeroplane, represented the future, or second fifty years, of flying.

TECHNICAL NOTES

This section of THE JOURNAL *is intended for short papers, comments upon published or unpublished papers with a limited circulation, interim results of research in hand, or notes for further research, or comments on notes already published, or letters raising technical points or asking questions. Contributions, which will be eligible for Journal Premium Awards, will normally be published within two months of being received.*

Optimum Conditions for the Operation of Airline Aircraft

by

ALAN H. STRATFORD, B.Sc.(Eng.), A.F.R.Ae.S.
(Superintendent of Performance and Analysis, British European Airways)

THE CONVENTIONAL method of assessing the direct costs or the aircraft type costs on a passenger mile or ton mile basis does not necessarily give a sufficient indication of the economic merit of a particular type of transport aircraft. It can be misleading when comparing aircraft of widely different design, and it does not indicate the best routes for effective airline exploitation.

The profit margin in relation to the fundamental cost or investment unit of the individual airline must be the ultimate yardstick of transport aircraft selection and this is here analysed with a view to providing further insight into the optimum conditions for potential profits. This study of the subject draws attention to the primary factors involved and suggests a criterion which can be simplified into a form valid for most airline economies.

REVENUE POTENTIAL AND THE LENGTH OF FLIGHT

The revenue earning capacity of a transport aircraft is a function principally of the payload ton miles that may be produced by it in a given time. This is the transport product which the airline organisation sets out to provide. The fare and freight rate structure is based on the passenger mile and the freight load/ton mile unit and it is for this reason that operating costs are reckoned on the same basis. It is generally found, however, that the "direct" cost of operation of a given type of aircraft is more closely associated with the time of flight than it is with the load carried or the miles flown. The costs per hour of operation, moreover, are reduced when the time in the air is spent in long stretches, since many items of cost, such as station and landing charges, as well as the time and fuel wasted on the airfield circuit, are constant factors that need be considered once only in each sortie.

A first condition therefore for the understanding of transport aircraft operating economy must be an assessment of the effect of flight time and stage length on the ton miles per hour of the transport product and on the specific costs of operation (pence per passenger- or ton-mile).

It will be assumed that the principles underlying the construction of the Payload-Range diagram are well known, but a typical presentation is shown in Fig. 3(*a*) for two aircraft *X* and *Y*, where the limitations of range and payload due to fuel tankage and landing and take-off weights are clearly shown.

It is important to note that the payload offered on a given stage will depend a great deal on the wind and air temperature conditions for which the fuel loads are computed and on the engine output and cruising altitudes for which the flight plan is prepared. Further, runway length limitations and adverse terrain may restrict take-off and landing weights so as to reduce payload on individual routes. These factors may be particularly penalising with turbine-engined transport aircraft in the presence of high ambient air temperatures.

Figure 1 shows a typical variation of flight time with block distance for a transport aircraft, in which a certain basic time interval is required for taxying, take-off, orbit, landing and time wasted in climb and descent. As block distance increases, some improvement in performance, due to increasing altitude and due to the reduced weight, will distort the linear form of the curve. A combination of the block speed of Fig. 1 and the appropriate payload-range diagram enables the curve of Fig. 2 to be drawn. This shows the variation of available ton miles per hour with the block distance flown. The maximum value *A* occurs at the maximum payload point of the payload-range diagram. The form of the curve is significant; it shows how rapidly the transport efficiency falls off on trips shorter than that giving the maximum payload point, in spite of there being no reduction in payload on shorter trips. It shows also, that the gain in block speed on longer flights can do little to correct the fall in economy due to the replacement of payload by cruising fuel. In the ideal case of an aircraft with a linear payload-range characteristic such as is shown in Fig. 3(*a*) and with no limitation due to fuselage or fuel tank capacity, the form of the ton mile versus range curve is as shown by the full line in Fig. 3(*b*). It can be shown from first principles, that the maximum ton mile point is at a block distance equal to half that at which the payload is reduced to zero, *i.e.* half the ultimate range with fuel reserves unconsumed.

Referring to Fig. 3(*b*) again; if *AB* is the maximum ordinate, then *OA* equals *AC*. In Fig. 3(*a*) will be seen

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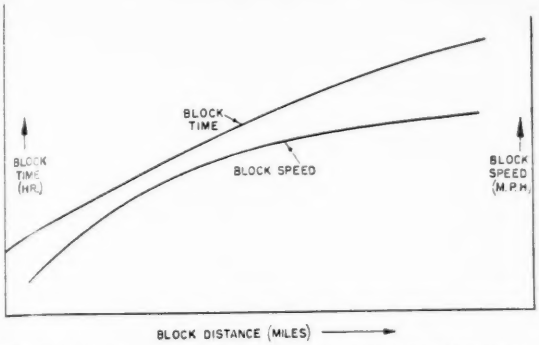

FIGURE 1. The effect of block distance on block time and block speed.

the corresponding payload carried and the effect of the fuselage capacity as well as the fuel capacity, on the ton mile curve of Fig. 3(*b*). The other lines shown dotted on these diagrams are for an aircraft of the same take-off weight, but with engines of high power and a low installed weight; they indicate the characteristics to be associated with propeller-turbine power plants, giving increased performance with a reduced installed weight at a considerably reduced specific range (or miles per gallon of fuel).

The most striking feature of the ton mile curves is clearly the fact that the maxima occur at block distances far greater than that indicated by the payload-range diagrams. It should be remembered however that the maximum range point for maximum payload will depend on the maximum landing weight of the aircraft or, when limited by fuselage capacity, by the seating arrangements or freight volumes provided. Generally speaking, the optimum block distance to operate a given type of aircraft lies somewhere between the greatest distance giving the maximum payload and the range giving the maximum ton miles, and hence between points *B* and *D* of Fig. 3.

RELATION OF REVENUE POTENTIAL AND COSTS PER FLIGHT

These considerations should enable us to obtain some insight into the relationship of revenue and costs so far as the optimum stage distance for the operation of a given aircraft is concerned. Since revenue is computed on the ton mile or passenger mile basis, the parabolic curves of Fig. 3(*b*) indicate the revenue earning capacity of an aircraft on various lengths of route.

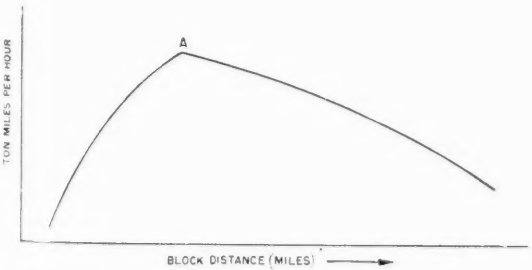

FIGURE 2. The effect of block distance on ton miles/hr.

Clearly, therefore, on a route corresponding to point *A*, a maximum revenue per flight is to be expected. For aircraft *X* a route of length *OA* may be said to provide the maximum earning potential.

If there is no marked variation in utilisation or change in the operating technique for flights of different stage length, it may be assumed that the "direct" costs of operation, *i.e.* those costs directly associated with the flight operation of the aircraft, are directly proportional to the time of flight. Hence, the time curve of Fig. 1 may be used as a "direct" cost variable for estimating the effect of block distance on these costs of operation, which we have here called the "direct" costs. In this way, we arrive at Fig. 4, from which it will be readily apparent that the maximum margin of revenue potential over "direct" costs occurs at a block distance rather less than that corresponding to the maximum ton miles per flight. The maximum margin will occur at a block distance *OF* at which the revenue and cost curves are parallel.

From an economic point of view, the "direct" or aircraft type costs of operation are only one part of the total costs and the true picture can only be presented when the total costs of operation are known as well. These additional costs are dependent on factors such as the route system and the general organisation of the airline concerned, and there is some justification for making simplified assumptions as to their variation. It should be sufficient to note here that total costs are

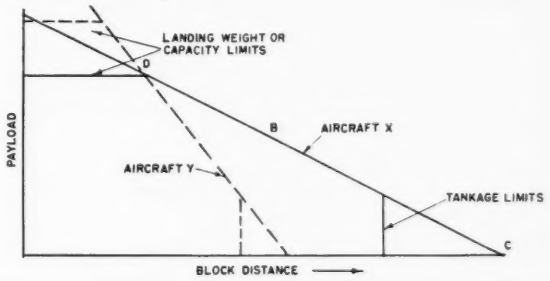

FIGURE 3(*a*). The effect of block distance on payload capacity.

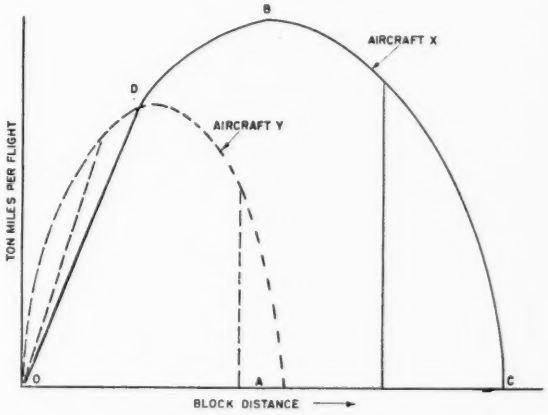

FIGURE 3(*b*). The effect of block distance on ton miles per flight.

in most cases approximately double the "direct" costs of operation on all routes, and if this assumption may be here accepted, it will have the effect of reducing still more the optimum route length for the maximum revenue margin. For particular airline studies more exact figures can be interpolated here and the variation from route to route may be known or can be readily assessed.

THE PROFIT OR LOSS PER COST INCURRED

It must be evident that the margin of profit (or loss) alone is not the true measure of optimum operation, since for longer flights where greater operating distances and costs are involved, a greater margin of profit should be expected. As a particular case which is of general application it is proposed here to study the variation in the margin of profit or loss in relation to the total cost incurred. It is convenient to resort to symbols since the result depends upon the form of the curves of cost and revenue versus block distance. If we may represent the variation of total costs with stage distance by a linear relation, then the cost C for any stage length R miles flown is given by $C = A + BR$, where A is the basic cost per flight which is independent of the distance flown (including all airline overheads, obsolescence of equipment and costs dissociated from flight operation but including the cost of take-off, landing and the lost time in taxying and let-down) and B is the average total cost per mile of those items directly related to the duration of flight or the stage length flown.

The revenue earned per flight may then be written as

$$\lambda\phi R\,(Q_0 - Rgd/V),$$

where no capacity limitations to payload are considered, and

λ = load factor
ϕ = revenue fare and rate factor (£ sterling/lb.)/mile
Q_0 = payload at zero block distance (lb.)
R = block distance (miles)
d = fuel density (lb./Imperial gallon)
g = fuel consumption (Imperial gallons/hour)
V = cruising speed (m.p.h.)

The margin of revenue over total costs per total cost incurred, which we here call the revenue margin, is conveniently written in terms of the symbols already set out as

$$\mu = \frac{\lambda\phi R\,(Q_0 - Rgd/V)}{A + BR} - 1.$$

It can then be shown, by differentiating μ with respect to R, that if λ the route load factor is kept constant then the block distance R for optimum operational economy is given by

$$R = \left[\left(\frac{A}{B}\right)^2 + \frac{A}{B}R_{\Gamma}\right]^{\frac{1}{2}} - \frac{A}{B}.$$

Thus, the optimum range for providing a maximum revenue margin per cost involved, depends upon the ultimate range of the aircraft R_{Γ} and the ratio of the cost factors A and B. Fig. 5 shows the variation of the optimum block distance for different values of the ultimate range and of the cost ratio A/B, and suggests that

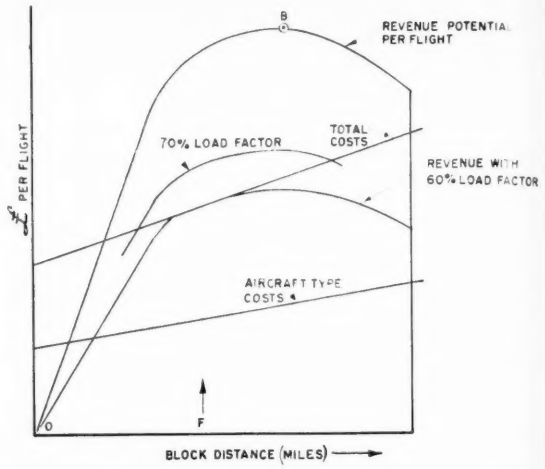

FIGURE 4. The effect of block distance on revenue potential and total costs per flight.

a range considerably less than that giving the optimum ton miles per flight will give the best return for airline operation. It will be noted that the actual load factor does not arise as a variable, but clearly if higher load factors can be achieved on stage distances other than the optimum indicated, some shift in the most desirable stage distance might result. Further, if the ratio of total to "direct" costs is known to vary from route to route this factor should be considered in the final analysis.

It may be shown that the profit margin per cost incurred μ may be equated to

$$\frac{\lambda}{\beta} - 1,$$

where β equals the break-even load factor and λ as before is the actual route load factor. Fig. 6 shows a plotting of μ for various values of λ, the actual load factor achieved, and β. When the operating costs for each route distance have been estimated for a new type of aircraft, it is possible to plot a curve of β versus the stage distance. Hence, on Fig. 6, we may cross-plot the break-even load factor for a given stage distance and the load factor estimated to be achieved on that same route or route distance. In this way, the loop curve shown has been drawn for an imaginary route system that might be operated by a new type aircraft, and on it the routes which are estimated to be able to earn a profit margin may clearly be seen.

LIMITATIONS AND VALUE OF THE ANALYSIS

The foregoing discussion, although based on a number of simple assumptions and taking no account of the limitations arising on individual aircraft types, does show that the direct or type cost index (pence per passenger- or ton-mile) is not a sufficient measure of transport aircraft economy. A consideration of revenue potential seems to be essential for a proper assessment of economy and the profit margin proposed here is thought to introduce this more exactly and as simply as does the break-even load factor.

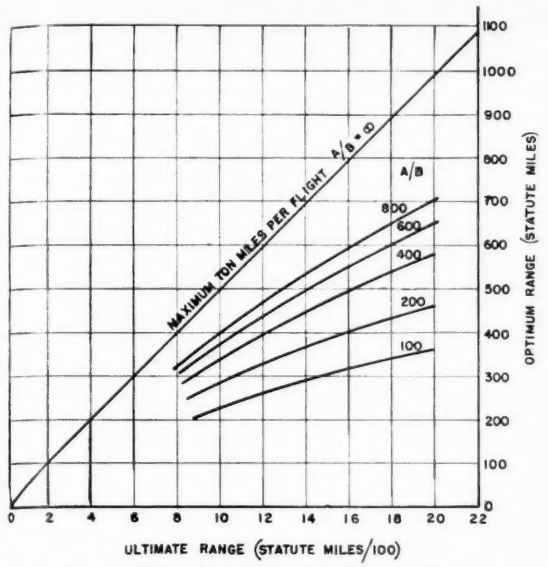

FIGURE 5. Effect of cost ratio A/B on optimum range.

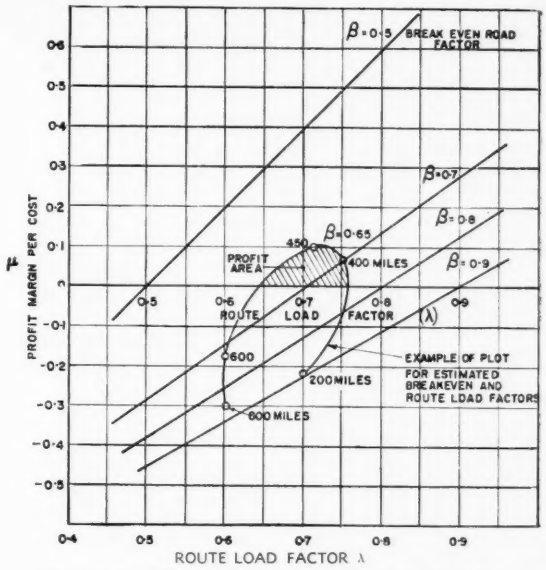

FIGURE 6. Effect of load factors on profit margin.

The analysis attempts to define the optimum use to which a given transport aircraft can be put, with particular reference to the length of flight. Some consideration will make it apparent that a small improvement in miles/gallon (*e.g.* through higher altitude operation of a turbine-engined aircraft) will enable the operator to reduce cruise fuel for the same sector distance and hence to increase the optimum range for operation. The increase in payload resulting must always improve the final economy, but it remains true that the improved aircraft will attain its optimum efficiency in terms of the profit margin on a greater block distance.

This study should assist in comparisons between turbo-jet and propeller-turbine aircraft. For two aircraft, the one jet propelled and the other propeller driven, each providing the same payload on the same block distance on a similar take-off performance, are essentially possessed of different ultimate ranges on account of the difference in their specific air range (miles/lb. of fuel). The shorter ultimate range of the jet transport is associated with a shorter optimum operating stage length, and generally a narrower belt of block distances within the specified profit margin. High fuel consumption in this way reduces considerably the economic flexibility of an aircraft. High fuel reserves, also associated with jet engines, not only reduce the transport product in proportion as the route payload is reduced but also decrease further the stage distance for the optimum revenue-earning capacity. It is not suggested that the criterion for economic merit given here is one of most value to all airlines, since net profit alone or in relation to capital invested may in individual cases provide a more significant parameter. The principles noted can be applied, however, to any particular case.

CONCLUSIONS

(*i*) The economic assessment of "direct" aircraft costs on a passenger mile or ton mile basis does not necessarily give a sufficient indication of the economic merit of an individual type of transport aircraft, nor does it show the best routes for airline exploitation, since revenue earning potential is not considered.

(*ii*) The profit margin per cost incurred, which is suggested as the ultimate criterion for many airline economies, can be simplified into an amenable parameter and is here proposed as a means of comparing aircraft types and as a method of providing some insight into profit potential on different routes.

The Normal Functions of Beam Vibration in Series Solutions of Static Problems

by

R. E. D. BISHOP

(*Engineering Laboratory, Cambridge*)

THE normal functions of beam vibration may be used in series to solve statical problems of beam flexure and the recent appearance of tables of these functions has rendered this method practicable. An outline is given of the procedure.

First received December 1952; revised 6th July 1953.

1. THE NORMAL FUNCTIONS

The simple equation of free flexural vibration of beams is

$$\frac{\partial^2 v}{\partial t^2} + \frac{EI}{A\rho}\frac{\partial^4 v}{\partial x^4} = 0 \quad . \quad . \quad (1)$$

where v is the displacement, EI the flexural rigidity and

$A\rho$ the mass per unit length. The separation of variables and the application of appropriate boundary conditions at the ends $x=0$ and $x=l$, gives the following normal functions $\phi(x)$.

(*a*) *Simply-supported*

$$\phi_n(x)=\sin\beta_n x$$

where $\sin\beta_n l=0.$

(*b*) *Clamped-free*

$$\phi_n(x)=\cosh\beta_n x-\cos\beta_n x-\varkappa_n(\sinh\beta_n x-\sin\beta_n x)$$

where $$\varkappa_n=\frac{\sinh\beta_n l-\sin\beta_n l}{\cosh\beta_n l+\cos\beta_n l}$$

and $1+\cos\beta_n l\cosh\beta_n l=0.$

(*c*) *Free-free*

$$\phi_n(x)=\cosh\beta_n x+\cos\beta_n x-\varkappa_n(\sinh\beta_n x+\sin\beta_n x)$$

where $$\varkappa_n=\frac{\cosh\beta_n l-\cos\beta_n l}{\sinh\beta_n l-\sin\beta_n l}$$

and $1-\cos\beta_n l\cosh\beta_n l=0.$

(*d*) *Clamped-clamped*

$$\phi_n(x)=\cosh\beta_n x-\cos\beta_n x-\varkappa_n(\sinh\beta_n x-\sin\beta_n x)$$

where $\varkappa_n$ and β_n are as for the free-free case.

(*e*) *Clamped-supported*

$$\phi_n(x)=\cosh\beta_n x-\cos\beta_n x-\varkappa_n(\sinh\beta_n x-\sin\beta_n x)$$

where $\varkappa_n=\coth\beta_n l$

and $\tan\beta_n l=\tanh\beta_n l$

(*f*) *Free-supported*

$$\phi_n(x)=\cosh\beta_n x+\cos\beta_n x-\varkappa_n(\sinh\beta_n x+\sin\beta_n x)$$

where $\varkappa_n$ and β_n are as for the clamped-supported case.

In each case the subscript n represents one of the successive roots of the relevant equation for $\beta_n l$. A discussion, with suitable tables, of these functions is given by Young and Felgar[6].

The normal functions $\phi_n(x)$ can all be shown (on integrating by parts) to possess the property of orthogonality, *i.e.*

$$\left.\begin{aligned}\int_0^l \phi_m\phi_n dx&=0 \quad (m\neq n),\\ &=K \quad (m=n).\end{aligned}\right\} \quad . \quad . \quad (2)$$

where K is a constant. It is found that

$$\left.\begin{aligned}&K=l/2 \text{ (simply-supported)},\\ &K=1 \quad \text{(all other types mentioned)}.\end{aligned}\right\} \quad . \quad . \quad (3)$$

It was shown by Rayleigh[3] that it can be inferred that *any* configuration of a beam (within the bounds of the theory of equation (1)) can be expressed in the form of a series of appropriate normal functions, *i.e.*

$$v=\sum_{n=1}^{\infty} A_n\phi_n(x) \quad (0\leqslant x\leqslant l) \quad . \quad . \quad (4)$$

and we are interested in finding the coefficients A_n so that, when the series converges rapidly, the first few terms may be used to calculate v approximately. For it is easily shown (by extending the simple theory of Fourier analysis*) that if the first m terms only are taken of such a series as (4), the best approximation is automatically obtained. That is, the coefficients A_n are such that the approximate function has the least mean square error of any that can be had from m terms of such a series.

2. LOADING FUNCTIONS

To find the coefficients A_n, it is first necessary to represent the loading $q(x)$ in series form; thus

$$q(x)=\sum_{n=1}^{\infty} B_n\phi_n(x) \quad (0\leqslant x\leqslant l). \quad . \quad . \quad (5)$$

Adopting the normal procedure of Fourier analysis, the orthogonality relations (2) are used to evaluate the coefficients B_n. It is found that

$$B_n=\frac{1}{K}\int_0^l q(x)\phi_n(x)\,dx. \quad . \quad . \quad (6)$$

For instance a point load W at the section $x=a$ $(0\leqslant a\leqslant l)$ is apparently expressible as

$$q=\frac{W}{K}\sum_{n=1}^{\infty}\phi_n(a)\phi_n(x) \quad . \quad . \quad (7)$$

and a counter-clockwise, point couple of moment M at this section yields

$$q=-\frac{M}{K}\sum_{n=1}^{\infty}\beta_n\phi_n'(a)\phi_n(x) \quad . \quad (8)$$

where $\phi_n'(x)=d\phi_n/d(\beta_n x)$. Neither of these two series converges so the signs of equality are not strictly justified. The defect, however, is easily removed by easing the requirement of *point* loading and approaching it indefinitely at a later stage in the determination of the quantities A_n when convergence will *not* be prejudiced. Thus, in writing equations (7) and (8), sufficient rapidity of convergence in the series for which they are to be used is anticipated. By setting $a=0$ or l in equations (7) and (8) it is easily shown that external reactions at a support or a clamp need not be calculated in this form of analysis.

Other forms of loading may be expanded into series form by means of equation (6). This will usually be easy enough and, when $q(x)$ is given analytically, it can often be effected quickly by the use of tables of integrals given by Felgar[2]. Numerical methods can also be used.

3. TRANSVERSE LOADING OF BEAMS

On substituting the series (4) and (5) into the equation

$$EI\frac{d^4v}{dx^4}=q \quad . \quad . \quad . \quad . \quad (9)$$

we find that, for termwise agreement, $A_n=B_n/(EI\beta_n^4)$ so that

$$v=\frac{1}{EI}\sum_{n=1}^{\infty}\frac{B_n}{\beta_n^4}\phi_n(x) \quad . \quad . \quad (10)$$

and the series, when curtailed, provides an approximation to v. Term-by-term differentiation is permissible so long as the resulting series still converges, *i.e.* so long

*see, for example, Sokolnikoff[4].

as β_n appears at least to the first power in the denominator of the general coefficient. In this way, series representations of slope, bending moment and shear force are obtainable.

4. BEAMS ON ELASTIC FOUNDATION

If a beam rests upon a foundation of modulus k, the deflection is given by

$$\frac{d^4v}{dx^4} + \frac{kv}{EI} = \frac{q}{EI} \quad . \quad . \quad . \quad (11)$$

By substitution we find

$$A_n = \frac{B_n l^4}{EI\,[(\beta_n l)^4 + kl^4/(EI)]} \quad . \quad . \quad (12)$$

so that the series for v can again be found.

The rate of convergence may be improved by a method due to von Kármán[5]. Noting that

$$\frac{1}{\beta_n^4} - \frac{1}{[\beta_n^4 + k/(EI)]} = \left(\frac{k}{EI}\right)\frac{1}{\beta_n^4\,[\beta_n^4 + k/(EI)]},$$

equation (12) may be written

$$A_n = \frac{B_n}{EI\beta_n^4} - \left(\frac{kl^4}{EI}\right)\frac{B_n l^4}{EI\,(\beta_n l)^4\,[(\beta_n l)^4 + kl^4/(EI)]} \quad (13)$$

The first member represents the deflection in the absence of the foundation (equation (10)) and may be a known result which can be stated exactly; the second represents a very rapidly converging series. This method of analysis is of great use when bending moments are sought as two differentiations of the deflection series might otherwise impair its convergence too seriously.

5. AXIALLY LOADED BEAMS

Only the simply-supported beam-column lends itself easily to the series procedure. This is because the equation of equilibrium contains the second derivative of v so that, when substituting the series for v into the equation, the property that $d^4\phi_n(x)/d(\beta_n x)^4 = \phi_n(x)$ cannot be exploited.

However, when the simply supported beam-column is treated in this way, very rapid convergence can again be obtained by a method comparable with that of equation (13).

6. PROPPED-AND CONTINUOUS BEAMS

The normal functions defined by the end conditions of a beam can be used to find the deflection even when intermediate reactions are unknown. The loading series (5) will then be of known form but will contain in its coefficients the m unknown reactions $R_1, R_2, \ldots R_m$. Suppose that it is judged that k terms of the deflection series warrant examination. The k coefficients A_n and the m reactions can be determined by assigning the deflections, expressed as curtailed series, at the supports; the supports may or may not subside. When the curtailed deflection series is forced into coincidence with the exact elastic curve at the supports, the least mean square error (in the sense of Section 1) is no longer obtained in general.

7. CONVERGENCE

Rate of convergence is crucial in deciding the usefulness of the series method. This can be examined by extending the theory of Fourier series (*see*, for example, Sokolnikoff[4]) to cover the several forms taken by $\phi_n(x)$. It is found that the rates of convergence are as in Table I for the worst conditions of loading and that, as q becomes a smoother function of x, matters steadily improve. A convergence rate of $1/\beta_n^3$ or better is desirable for the purpose of approximating.

TABLE I

Series	*Power of β_n in denominator of general coefficient if loading is:—*	
	Point couple	*Point force*
Deflection	3	4
Slope	2	3
Bending moment	1	2
Shear force	–	1

8. CONCLUSIONS

There is nothing original in stating that the normal functions of beam vibration can be used in statical beam analysis. But this has only recently been made a practical proposition by the publication of suitable (and very well drawn-up) tables. The method amounts to a simple extension of Fourier analysis, of which the simply-supported beam theory is clearly a special case. A more general discussion of series solutions of beam problems is given by Duncan[1].

The theory given is by no means exhaustive. For instance, these series can be used for energy considerations in conjunction with Castigliano's theorem. Again, influence coefficients are readily expanded in series form; and so on.

The normal functions of beams in free vibration, when allowance is made for shear, have not been tabulated. It is possible that, if available, they would often offer the best means of finding static deflections in which shear plays a part.

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CORRESPONDENCE

Oscillatory Occurrences in Ball Bearings

27th March 1953

Sir,—Dr. Frenkel (December 1952 Journal, p. 885) has made a valuable contribution to the literature on rolling bearings by drawing attention, for the first time, to the conditions giving rise to oscillatory phenomena in the motion of rolling elements in bearings, and by deriving a system of design formulæ, and designs for their elimination.

The dynamics of ball motion in ball bearings have hitherto been of little concern to the designer, but experience shows that existing concepts of ball bearing design produce results that are far from satisfactory, in spite of great attention to tolerances, finish, assembly, and so on.

That the faults are fundamental, and due to inability to take into account the dynamics of ball motion, would appear from a little consideration—in the light of Dr. Frenkel's paper—of the prevailing trend in ball bearing design in the last decades. Increasing use is made of deep-groove *radial* ball bearings—which under *axial* load act as low-angle angular-contact bearings (*i.e.* having a small angle between the rolling axis of a ball and the bearing axis)—even for the carrying of heavy axial loads at high and medium speeds, despite the fact that, owing to the large angle between the external load and the line of loading of individual balls, extremely high stresses are set up in the areas of contact. The paper clearly shows why this trend has been forced upon bearing designers by the exigencies of practice because the smaller the angle of contact, *i.e.* the more nearly a bearing is a radial bearing, the higher is the speed at which the uncontrolled dynamics of the ball motion destroy the bearing after only a short period of operation. Inability to take into account the dynamics of ball motion has forced designers to adopt an application of radial ball bearings which is thoroughly unsound from the standpoint of the statics of a ball bearing as a load-carrying element, and which leads to very heavy and inefficient designs and installations.

At the same time, this trend of design away from the statically sound high-angle angular-contact bearings for carrying thrust loads shows that, contrary to accepted opinion, high stresses in the contact areas are much less destructive to bearings than the oscillatory phenomena of uncontrolled ball motion revealed by the paper. The importance of Dr. Frenkel's line of attack on the problem is thus clearly demonstrated.

Furthermore, it appears that at the present stage of engineering development, the absolute limit of this trend in bearing design has been reached with the recent great increases in high-speed, high-load applications, *e.g.* in gas turbines, where serious troubles have been encountered. The only solution to the problems encountered would seem to be to take into account in design the dynamics of ball motion as indicated in Dr. Frenkel's work, which at the same time also makes possible a return to sound principles of statics in bearing design.

A properly designed bearing would: —

(*i*) have a definable life, of practical length at high speed and load.

(*ii*) have a low "natural" running temperature, thus minimising lubrication and cooling requirements.

(*iii*) produce little noise.

(*iv*) be comparatively unaffected by the superimposed dynamics of the installation.

None of these requirements has so far been achieved in high-speed applications where the bearing dynamics become prominent.

The author's revelation of the oscillatory phenomena in ball motion illuminates the troubles occurring under the headings (*i*)-(*iv*) in conventional bearings, and would seem to clear up some hitherto puzzling features of practical experience. For example, the great "scatter" in the performance of identical bearings (as much as 1,000 per cent. in a series run in similar conditions) which has so far been vaguely attributed to variations in surface finish and dimensions, becomes logically understandable when it is envisaged how very small variations in dimensions can cause large differences in oscillatory phenomena, which have themselves a much greater influence on bearing life than static stresses. Further, as high-frequency impulses and excessive sliding in the contact areas are a feature of conventional high-speed ball bearings, the high operating temperatures with consequent attendant cooling and lubrication problems are not surprising, nor is the fact that the noise emanating from high-speed bearings is such as to cause acute discomfort to bystanders. High frequencies predominate in this noise, and its analysis, which seems never to have been attempted, would be interesting in relation to the oscillations in the ball motion.

A further apparent paradox of experience, which is resolved by the paper, is the short bearing "life" under comparatively light loads (equation (55) on gyroscopic effect, suggests one factor). However, while gyroscopic effect would be taken care of by higher loadings, if it were the only trouble, the author shows that the main cause of the oscillations is the "pseudo-gyroscopic effect," which acts under even the heaviest loads, and produces a rotation of the ball about the axis tangential to the ball path and about that radial to the ball path—similarly to the gyroscopic effect.

This new conception, the "pseudo-gyroscopic effect," seems very important and could bear elucidation, perhaps with reference to the text on pp. 897 and 898. However, the picture of the ball motion due to it, with oscillating rotations about the *X*- and *Y*-axes (Fig. 5), and consequent high-frequency impulses of ball against track and cage, seems very fruitful. It throws light, for example, on the hitherto unexplained, but well-known phenomenon of sinusoidal "tracking," which shows as bands of pitting on the race in extreme cases; it shows further how the balls of a race, each having oscillations in a different phase, can destroy a cage by impulses both in the radial and circumferential directions—as occurs too often in practice with high-speed bearings.

Could the author perhaps throw more light on the effects of friction in the areas of contact in all these phenomena, perhaps on a comparative basis between the conditions in a bearing with oscillations, and one with trouble-free ball motion?

The paper makes it clear that the important condition (*i*) of Case III, p. 901, can be achieved only by balancing the various couples acting on a ball, both at constant speed (equations (76), (77), . . . leading to (85)), and at variable shaft-speed (equation (87), etc. . . . derived in Ref. 1). All

these equations require a definite angle, ϑ, apparently increasing with speed, between the axes of symmetry of opposing groove profiles, *i.e.* these "axes of symmetry" should *not* be in the same straight line.

It would also be helpful if the author would indicate more precisely than in expressions (92) and (93) how the functions of the theory of elasticity of Hertz are intended to be used in design according to his system.

The author has derived his system of design formulæ to provide individual bearing designs in each of which is eliminated the oscillatory phenomena over a range of conditions of speed and load. However, the question arises whether any particular set of dimensions calculated in this way can be reproduced with sufficient accuracy in quantity production; or, in other words, could the author say how the tolerances at present obtained in bearing manufacture, or say, variations in the temperature of bearing installation, would affect the performance of a bearing designed according to his system of formulæ?

In the light of these remarks about the present trend in bearing design, the double bearing construction proposed by Dr. Frenkel (Figs. 8 and 8A of Ref. 1; *see* also Ref. 2) is the very ingenious solution of the problem of keeping the balls in contact with, and under control from, both tracks in a radially-loaded bearing. In existing single-row deep-groove ball bearings, loaded radially, the balls are unloaded and thus out of control over at least half the ball path. The static stresses involved in the proposed construction would certainly be less than those in a radial ball bearing carrying thrust load, owing to the smaller angle between the direction of the external load and the load lines of the individual balls, and would be well worth incurring to eliminate the destructive oscillatory phenomena.

Indeed one may go so far as to say that in the interests of safety and efficiency single-row deep-groove ball bearings for high duty application involving radial loads *must* be superseded by properly designed double-row angular-contact bearings.

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R. J. MILLSON, A.F.R.Ae.S., A.M.I.Mech.E.

7th May 1953

Dr. Frenkel's reply—

I much appreciate Mr. Millson's valuable contribution which confirms from practical experience my conclusion, theoretically derived, that the oscillatory phenomena of uncontrolled ball motion are far more detrimental to bearing life and performance than high contact stresses due to loading on the balls—a conclusion which also led me to develop the double-row bearing constructions mentioned in the contribution (Ref. 2). Shortage of space prevents my doing justice to the many stimulating questions raised, but I would indicate briefly the solution to the important question: How to maintain the conditions for the elimination of oscillatory phenomena in all bearing constructions which, owing to the limitations of accuracy of quantity production, temperature effects, wear and so on, deviate within predetermined tolerances from the design configuration. This problem, incidentally, arises with all machinery subject to oscillatory occurrences, particularly at high speed (*e.g.* aircraft, gas turbine blade vibrations, and so on).

In the general case of a construction with n dimensional variables for which the conditions for a required performance are expressed in a system of m design equations ($n>m$), the solution to this problem involves the derivation of new design-equations which interrelate the $n-m$ previously independent dimensional variables.

The solution involves first distinguishing between a first class of these dimensions, for which the ratio of maximum deviation to the exact dimension has a determining influence on the performance, and a second class of these dimensions for which this is not so.

The general solution begins with the solution of a special case, to provide a reference case. With the aid of the "transformatory operations" of mathematics, all cases will then be reduced to this reference case (A):—

(A) The special case is that of a dimension q_1 which occurs only in one design-equation, this equation also containing a number of other dimensions q_2, q_3, q_4, *e.g.*

$$f_{(1)}(q_1, q_2, q_3, q_4)=0 \quad . \quad . \quad (1)$$

The two requirements of the problem then are:—

Condition I: That equation (1) should provide the same condition for the required performance over a range of variation of dimension q_1 from $(q_1-\Delta q_1)\leqslant q_1\leqslant(q_1+\Delta q_1)$.

Condition II: That the deviation Δq_1 from the exact dimension q_1 be *completely independent* of all other dimensions q_2, and so on, and of variations of these dimensions, because the deviations Δq_1, due for example to manufacturing tolerances, are completely independent of the other dimensions.

Because of these two conditions, besides equation (1), the equation

$$f_{(1)}[(q_1+\Delta q_1), q_2, q_3, q_4]=0 \quad . \quad . \quad (2)$$

must be valid, which is a contradiction to equation (1) because this equation requires that a variation of q_1 should proceed with a corresponding variation of at least one other dimension.

The resolution of this contradiction requires further conditions which are obtainable by expressing equation (2) as

$$f_{(1)}[(q_1+\Delta q_1), q_2, q_3, q_4]= f_{(1)}(q_1, q_2, q_3, q_4)+\Delta q_1\frac{d}{dq_1}[f_{(1)}(q_1, q_2, q_3, q_4)]+ +\frac{\Delta q_1^2}{2}\frac{d^2}{dq_1^2}[f_{(1)}(q_1, q_2, q_3, q_4)]\ldots=0 \quad . \quad (3)$$

This yields, as conditions for both equations (1) and (2) to be valid,

$$\frac{d}{dq_1}[f_{(1)}(q_1, q_2, q_3, q_4)]=0 \quad . \quad . \quad (4)$$

$$\frac{d^2}{dq_1^2}[f_{(1)}(q_1, q_2, q_3, q_4)]=0 \quad . \quad . \quad (5)$$

and so on. The number of these equations applicable, *i.e.* the order of differentiation necessary, depends on the magnitude of Δq_1, the maximum deviation of q_1, and is denoted the "*order of stability*," as a more general case of the formulation introduced with regard to stability in my paper in the *Proceedings of the Institution of Mechanical Engineers* for March 1953 (*see* equation (29)).

(B) Consider now the general case of a dimension q_1 in an equation

$$f_{(2)}(q_1, q_2, q_3, p_1, p_2)=0 \quad . \quad . \quad (6)$$

where, in contra-distinction to Case (A), q_1 is also interrelated with other dimensions p_1, p_2, occurring in equation (6) by several other design-equations of the system, such as for example

$$f_{(3)}(q_1, p_1)=0 \quad . \quad . \quad . \quad (7)$$

Proceeding for q_1 in equation (6) as in the reference equation (1), would give some new equations

$$\frac{d}{dq_1}[f_{(2)}(q_1, q_2, q_3, p_1, p_2)]=0 \quad . \quad . \quad (8)$$

a second order equation . . (9)

and so on, as additional conditions.

However, such equations (8), (9), . . . provide the conditions through which Δq_1 is independent of the other dimensions such as p_1, p_2, and variations thereof, *only* for equation (6), but equations (8), (9), . . . do *not* provide the conditions for Δq_1 to be independent of the other dimensions p_1, p_2 for the other equations of the system, such as equation (7), which also contain p_1, p_2. This leads to a contradiction because, for example, equation (7) requires that a variation of q_1 should proceed with a corresponding variation of p_1, and so on.

To resolve this contradiction between Condition II and the other equations such as (7) in which q_1 and the other dimensions p_1, p_2 of equation (6) also occur, the method is to substitute in equation (6) in terms of q_1, and so on, with the aid of the other equations such as (7), for all the dimensions p_1, p_2 . . . which occur together with q_1 also in the other equations. This gives *finally* an equation of the form

$$F_{(2)}(q_1, q_2, q_3, q_4)=0 \quad . \quad . \quad (10)$$

equivalent to the reference equation (1), which contains only q_1 and dimensions with which it is not connected by any other equation of the original system—as required by Condition II.

By proceeding with equation (10) along the lines indicated for the reference Case (A), which leads to additional equations

$$\frac{d}{dq_1}[f_{(2)}\, q_1, q_2, q_3, q_4)]=0 \quad . \quad . \quad (11)$$

a second order equation . . (12)

and so on, and with similar treatment of other dimensions of the first class, one can derive, for example, for the system of design-equations for the elimination of oscillatory phenomena in ball bearings, the additional design-equations necessary for this performance to be stable within predetermined tolerances of the calculated exact configuration.

Shortage of space unfortunately does not permit me to be more specific on this development, for example, on the method of distinguishing between the first and second class of dimensions, and so on.

For the same reason I am unable to present my new representation of the Hertzian deformation-equations, which permit direct determination of related quantities, in contrast to the calculations of successive approximation previously necessary;—or to elucidate the oscillations due to " pseudo-gyroscopic effect," and so on.

M. S. FRENKEL.

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Reviews

THE THEORY OF HOMOGENEOUS TURBULENCE. *G. K. Batchelor.* 197 *pp.* 29 *diagrams. Cambridge University Press* 1953. 25*s.*

Dr. Batchelor and his colleagues at Cambridge are well known for their stimulating research on turbulence, both in theory and by experiment. Although the Cambridge work is well reported there has existed for some time the need for a complete account of the present state of knowledge. In fact the need is twofold since, as Dr. Batchelor states in the preface, "the surge of progress which began immediately after the war has now largely spent itself, and there are signs of a temporary dearth of new ideas."

Although the conception of homogeneous turbulence (where the average properties are independent of their position in the fluid) is an idealised one, there are nevertheless cases in practice where the turbulent motion can be so approximated. In some of these cases restrictions on the directional symmetry of the average properties of the turbulent motion arise, and in the simplest of these, the turbulence can be assumed both homogeneous and isotropic (where the average properties are independent of the position and direction of the axes of reference). Typical practical cases are the turbulence behind grids and in shear flow turbulence, where experiment indicates that over a restricted range of eddy sizes the flow tends to isotropy. It is therefore paramount to an understanding of such problems as boundary layer, wake and jet turbulence that the laws of homogeneous turbulence should be established. Dr. Batchelor has presented his work with this aim in view. It represents a fine balance between the mathematical analysis and descriptive physical processes.

After a brief historical introduction, Chapter 2 deals with the representation of turbulence by taking averages, mean values of velocity products, correlations, spectrum tensors and Fourier analysis. The kinematics of homogeneous turbulence are discussed in Chapter 3 and in particular the velocity and vorticity correlations and the energy spectrum function. Two linearised problems of great practical interest are presented in Chapter 4. These are (*i*) the change in turbulence on passing through a gauze and (*ii*) the effect of a sudden distortion of a turbulent stream. The dynamics of the decay of turbulence starting from the Navier-Stokes equations, together with the flow of energy as a result of pressure, inertia and viscous forces, the role of the big eddies and the final period of decay are discussed in Chapter 5. The universal equilibrium theory, pioneered by Kolmogoroff, is presented in Chapter 6 with brief mention of its application to many physical fields in which turbulent motion arises. Chapter 7 gives the results of experiments on the turbulent motion behind grids. These results are used to form a basis for the theory of the decay of the energy containing eddies and in particular to the spectrum function for large wave numbers. In his final Chapter, Dr. Batchelor describes the probability distributions of the turbulent velocity and their importance in the framing of a model of the structure of turbulence.

A very full list of references is given, together with a combined subject and author index. This book is well provided with diagrams, records of experimental data and numerous footnotes, all of which assist the reader to attain a close understanding of the text. No scientific worker engaged on fluid motion problems, and indeed on any work where a knowledge of turbulent motion is essential, should miss the opportunity of studying this monograph either in part or in its entirety.

Dr. Batchelor should be congratulated on his able presentation of a very difficult subject.—G. M. LILLEY.

ON BEING A BIRD. *Philip Wills.* 232 *pp. Photographs and drawings. Max Parrish* 1953. 15*s.* 6*d.*

Why should a respectable business man spend his spare time in a glider? Philip Wills explains in a delightfully easy style and with a pleasing sense of humour, the fascinations of the sport at which he is now the world champion.

Since he tired of flying a light aeroplane twenty years ago he has been the most successful sailplane pilot in this country. His book includes accounts of his flights both in Britain, among the Alps, with vultures in South Africa and during the World Contest in Madrid in 1952. Several of these accounts have been published before but are collected for the first time and linked by technical matters explained non-technically in the Willsian manner with the aid of some well-drawn diagrams.

Although the flying of the sailplane is essentially a lonely—often frighteningly lonely—pastime, the author makes clear the dependence of the pilot on his ground crew and on the club members who provide the launching facilities. Kitty Wills, to whom the book is dedicated, has contributed immensely to her husband's success by towing his trailer many thousands of miles to retrieve him after his flights. Only the pilot, however, can describe his feelings while sliding silently between 10,000 feet high snow covered peaks, inside a dark cumulo-nimbus cloud or over the English Channel in a sailplane during the Battle of Britain—and he does it well.—ALAN YATES.

FUELS AND COMBUSTION. *Marion L. Smith and Karl W. Stinson. McGraw-Hill 1952. 340 pp. Index. 55s. 6d.*

This book is intended for engineers and particularly undergraduate engineering students. While American undergraduates and engineers will find that the combustion of solid liquid and gaseous fuels is excellently presented this cannot be said of the treatment of the sources, types and properties of the fuels themselves, which is not nearly so authoritative and, indeed, is open to criticism. The reader could also be pardoned if he were to assume from the almost complete lack of reference to them that outside America, fuels hardly exist or processes and equipment for utilising them. This rather parochial outlook runs throughout the book except where it deals with research into the nature of combustion; in consequence the book gives an impression of some lack of balance.

The opening chapter contains numerous factual errors. It repeats the well-worn statement that peat is the progenitor of coal and has been progressively altered to give lignite, bituminous coal and finally anthracite. In

fact peat is derived from a quite different type of vegetable remains from those which have given rise to coal. Not all coal has been produced from the same vegetable matter and the routes followed during coalification have not been identical. In a book of this type, the banded structure of coals should have been discussed in more detail, and some account given of the petrology of coal. This would have avoided the perpetuation of the peat theory.

Reference can only be made to a few other points in this Chapter. For example Figs. 1-5 give a percentage composition for anthracite which in total exceeds 100. On p. 26 kerosine and gasoline are ascribed the same percentage composition. More serious errors suggest imperfect acqaintance with the subject under discussion, for example, during ultimate analysis (p. 12) the carbon dioxide evolved is said to be absorbed before the water, whereas the reverse is the case. The descriptions of town gas and coke oven gas manufacture (pp. 29 and 30) are inadequate and in fact misleading. For the former a temperature of 2,700°F. is too high and for the latter 1,200-2,000°F. is too wide a range and the mean is too low. Even more serious errors occur in connection with synthetic fuels (p. 33). Oil shale is loosely spoken of as containing oil whereas it contains a complex substance kerogen which only breaks down to yield oil on distillation. On p. 35, the flow sheet in Figs. 1-23 is said to portray an existing Fischer-Tropsch plant whereas it is completely unlike any plant now erected or likely to be in the future. It shows pulverised fuel being fed to a fluidised gasification chamber operating at 2,100°F. at which the ash would become sufficiently sticky to cause fluidisation to break down.

In the succeeding chapters however, on stoichiometry and thermo chemistry, the authors are on firmer ground and give a clear and accurate exposition which, in conjunction with working out the problems posed, will provide undergraduates (and others) with a very good grip of this type of work. On the chemistry of combustion and the properties of fuels the book is excellent (apart from the narrow U.S.A. outlook already referred to). Gas receives rather scant treatment and it might have been better to discuss here, the effect of gravity, hydrogen percentage, etc., rather than in connection with the design of burners later in the book. Combustion apparatus is particularly well treated from the purely American point of view. A comparison of operating features of solid fuel stokers is very valuable (pp. 277 and 278). Gas turbines could have received a little more attention.

The book is well produced and notably free from printers' errors but certain figures show inferior draftsmanship, *e.g.* Figs. 1-10 and Figs. 2-3. A number of loose large scale charts useful for hydrocarbon combustion calculations are included.—F. A. WILLIAMS (Ministry of Fuel and Power).

WORLD AIRLINE RECORD. 1952 EDITION. *Roy R. Roadcap and Associates. Chicago* 1952. 400 *pp. Maps and diagrams.* $9.75. *Reviewed April* 1953.

The publishers feel that the review of this book which was published in the April 1953 JOURNAL has over-emphasised minor inevitable inconsistencies and may have left the impression that the book is unreliable. They point out that the information given was supplied by the carriers and that it is inevitable that some of this information may not be absolutely up to date at the time of publication. In addition, the spelling of place names will vary with the nationality of the carrier concerned.

Additions to the Library

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*—— TABLES OF SUPERSONIC FLOW AROUND CONES. 1947.

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Reports

AERODYNAMICS

Boundary Layer

See also Wings and Aerofoils

The calculation of the profile drag of aerofoils and bodies of revolution at supersonic speeds. A. D. Young. Cranfield Report No. 73. (April 1953.)

The effects of viscosity on the aerodynamic characteristics of wings and bodies at supersonic speeds can be assessed if we can calculate (*a*) the development of the boundary layers in the laminar and turbulent states, (*b*) the interaction of the boundary layers and main stream away from the neighbourhood of shock waves, (*c*) the effects of shock wave-boundary layer interaction. Comprehensive methods are developed and discussed for dealing with problems (*a*) and (*b*), problem (*c*) is discussed in the light of existing experimental data but more systematic data are required before quantitative prediction of shock wave-boundary layer interaction effects in any particular case can be confidently made.—(1.1).

The numerical solution of certain differential equations occurring in Crocco's theory of the laminar boundary layer. S. Kirkby and T. Nonweiler. Cranfield Report No. 74. (May 1953.)

A numerical method is described for the solution of certain differential equations which result from the application of Crocco's transformation to the laminar boundary layer equations appropriate to high supersonic Mach numbers. Solution is obtained by continuous application of a rapidly convergent relaxation process to a pair of simultaneous differential equations, for which one of the boundary conditions is a first derivative.—(1.1.1).

Discussion of boundary-layer characteristics near the wall of an axial-flow compressor. A. Mager, J. J. Mahoney and R. E. Budinger. N.A.C.A. Report 1085. (1952.)

Boundary-layer velocity profiles on the casing of an axial-flow compressor behind the guide vanes and rotor were measured and resolved into two components: along the streamline of the flow and perpendicular to it. By use of these results and the momentum-integral equations, the characteristics of boundary layer on the walls of axial-flow compressor are qualitatively discussed.—(1.1.4. × 1.5.2).

Compressible Flow

See also Wings and Aerofoils

A comparison of calculated and measured base pressures of cylindrically based projectiles. W. F. Cope. A.R.C. Current Paper No. 118. (May 1952, published 1953.)

A comparison of recent tests with the method given in the N.P.L. Report Eng. Div. 222/46, "Calculation of Reynolds number effect on projectiles at supersonic speeds" by W. F. Cope, which is reproduced as an Appendix to this paper.—(1.2.3).

Experiments with static tubes in a supersonic airstream. Parts I and II. D. W. Holder, R. J. North and A. Chinneck. R. & M. 2782. (July 1950, published 1953.)

Systematic tests have been made at a Mach number of 1·6 on a family of static tubes. The variables which have been investigated are the shape of the nose, the distance of the holes downstream, and the inclination of the tube to the flow. Pressure measurements have also been made in the vicinity of a shock wave and close to a wall.—(1.2.3 × 31.2).

Ebene Plattengitter bei Uberschallgeschwindigkeit. R. M. El Badrawy. Mitteilungen Inst. f. Aero. Nr. 19, Zurich. (1952).

The supersonic thickness drag of rectangular wings with linear spanwise taper in thickness. K. Walker, Jr. Douglas Report No. SM-14739. (March 1953.)

The supersonic thickness drag for the rectangular wing with linearly varying thickness ratio (symmetrical about root chord) is studied. The airfoil profiles considered have symmetrical modified double-wedge sections with constant thickness over a variable fraction of the chord length or biconvex sections.—(1.2.3 × 1.10.1.2).

A study of second-order supersonic flow theory. M. D. van Dyke. N.A.C.A. Report 1081. (1952.)

Second-order solutions of supersonic-flow problems are sought by iteration, using the linearised solution as the first step. For plane and axially symmetric flows, particular solutions of the iteration equation are discovered which reduce the second-order problem to an equivalent linearised problem. Comparison of second-order solutions with exact and numerical results shows great improvement over linearised theory.—(1.2.3).

Internal Flow

The secondary flow in curved pipes. R. W. Detra. Mitteilungen Inst. f. Aero. Nr. 20, Zurich. (1953).

The study includes an experimental investigation of the secondary flow phenomenon followed by a theoretical investigation of the initial or starting phases of the secondary flow in slightly bent pipes made through an application of the equations of motion of an incompressible inviscid fluid.—(1.5.1).

A rapid method for use in design of turbines within specified aerodynamic limits. R. H. Cavicchi and R. E. English. N.A.C.A. Technical Note 2905. (April 1953.)

Basic thermodynamic relations were applied to axial-flow turbine designs for which specified aerodynamic limits were set in order to evolve a rapid method of determining turbine velocity diagrams. The method is presented in both chart and tabular form.—(1.5.3).

Loads

The zero-lift drag of a slender body of revolution (N.A.C.A. RM-10 research model) as determined from tests in several wind tunnels and in flight at supersonic speeds. A. J. Evans. N.A.C.A. Technical Note 2944. (April 1953.)

Presents zero-lift drag data of an N.A.C.A. RM-10 slender body of revolution with and without stabilising fins attached. The results from several wind tunnels and in flight are compared. The results cover a Reynolds number range from about 1×10^6 to 40×10^6 for the wind-tunnel models and 12×10^6 to 140×10^6 for the flight models. The Mach numbers covered include 1·5 to 2·4 in the wind tunnels and 0·85 to 2·5 in flight.—(1.6).

Performance Estimation

The effect of compressibility on the attitude of aircraft in rectilinear flight. K. J. Lush. R. & M. 2776. (March 1948, published 1953.)

Stability and Control

The effect of slipstream on the longitudinal stability of multi-engined aircraft. D. E. Morris and J. C. Morrall. R. & M. 2701. (November 1948, published 1953.)

Flight measurements of longitudinal stability power-off and power-on made on numerous aircraft have been analysed and a generalised curve for estimating the contribution of slipstream to longitudinal stability, applicable to both flaps-up and flaps-down cases, has been derived. Using this curve the change in stability due to slipstream at a given value of C_L can be estimated with a probable error of less than ±0·02 in the position of the neutral point.—(1.8.2).

NOTE:—*The figures in parenthesis at the end of each Summary are for office use only.*

Measurement of pitching moment due to yaw on the CA-22 elementary trainer. A. S. Bennett, A.R.L. Australia, Aerodynamics Note 115. *(January* 1953.)

Pitching moments due to yaw were measured for the complete model of the CA-22 elementary Trainer and found to be of such magnitude as to necessitate the use of excessive stick forces in certain manoeuvres particular the slow roll. Various modifications were then made to the model to reduce the large moment changes. These modifications and their corresponding effect on the stability of the aircraft are described in this report.—(1.8.2).

Theoretical damping in roll and rolling moment due to differential wing incidence for slender cruciform wings and wing-body combinations. G. J. Adams and D. W. Dugan. N.A.C.A. Report 1088. (1952.)

A method of analysis based on slender-wing theory is developed to investigate the characteristics in roll of slender cruciform wings and wing-body combinations. The method makes use of the conformal mapping processes of classical hydrodynamics which transform the region outside a circle and the region outside an arbitrary arrangement of line segments intersecting at the origin. The method of analysis may be utilized to solve other slender cruciform wing-body problems involving arbitrarily assigned boundary conditions. —(1.8.1).

Study of motion of model of personal-owner or liaison airplane through the stall and into the incipient spin by means of a free-flight testing technique. R. W. Stone, Jr., W. G. Garner and L. J. Gale. N.A.C.A. Technical Note 2923. *(April* 1953.)

This paper presents the motion of a dynamic model through the stall and into the incipient spin. The results indicate that, after the initial stall, the model became unstalled, inverted, and assumed very low angles of attack before restalling and entering the incipient spin. Altitude loss and angular velocities were relatively small during the early part of the motion and indicated that this time would be the optimum time to terminate the motion by control movement. —(1.8.3).

Wings and Aerofoils

See also Compressible Flow

Some experiments on the flow in the boundary layer of a 45° *sweptback untapered wing of aspect ratio* 4. *K. Emslie, L. Hosking, W. S. D. Marshall. Cranfield Report No.* 69. *(February* 1953.)

Visual methods have been used together with a yawmeter to illustrate conditions of flow in the boundary layer over a sweptback wing.—(1.10.2.2 × 1.1).

The application of the polygon method to the calculation of the compressible subsonic flow round two-dimensional profiles. L. C. Woods. Current Paper No. 115. *(June* 1952, *published* 1953.)

This paper sets out the method now used by the author of applying the polygon method to the calculation of the compressible subsonic flow round two-dimensional aerofoils. Tables have been constructed which can be used for all aerofoil shapes, putting the polygon method on the same footing numerically as Goldstein's " Approximation III " for incompressible flow. A method of calculation lift and moment coefficients, and their rates of change with incidence is also given. As an example the velocity distribution and the rates of change of the lift and moment coefficients with a are calculated for the aerofoil R.A.E. 104.—(1.10.1.1).

Wind-tunnel test of the stalling properties of an 8 *per cent. thick symmetrical section with nose suction through a porous surface. R. C. Pankhurst, W. G. Raymer and A. N. Devereux. R. & M.* 2666. *(June* 1948, *published* 1953.)

The stalling properties of an 8 per cent. thick symmetrical aerofoil with large leading-edge radius of curvature and continuous (distributed) suction over the nose have been tested in the 4 ft. No. 2 wind tunnel of the National Physical Laboratory.—(1.10.2.1 × 1.1.5).

Measurements of maximum lift on 26 *aerofoil sections at high Mach number. Part I. J. A. Beavan, et al. Part II. R. J. North and Miss P. M. Burrows. R. & M.* 2678. *(January* 1948, *published* 1953.)

The lift on a number of aerofoil sections mostly of 2 in. chord has been determined over a wide range of incidence and Mach number by measuring the pressures on the walls of the 20 × 8 in. high speed tunnel.—(1.10.2.1 × 1.2.1).

High-speed tunnel tests of a 5 *per cent. chord dive-recovery flap on a N.A.C.A.* 0015 *aerofoil. D. A. Clarke. R. & M.* 2689. *(June* 1948, *published* 1953.)

Pressure plotting tests were made in the Royal Aircraft Establishment high speed tunnel on a parallel wooden N.A.C.A. 0015 wing with dive-recovery flap. The Mach number was varied between 0·30 and 0·80, and the Reynolds number was kept constant at $1{\cdot}4 \times 10^6$. All combinations of the following were tested: flap position 0·2c, 0·3c, 0·4c; flap angle 20°, 40°; incidence 0°, 4°. The flap-chord/wing-chord ratio was 0·05. The report presents a general picture of the action of a dive-recovery flap on a wing. The data are, however, too limited to permit the formulation of general design recommendations.—(1.10.2.1).

Low-speed wind-tunnel tests on two 45° *sweptback wings of aspect ratios* 4·5 *and* 3·0 *(models A and B). J. Trouncer and G. F. Moss. R. & M.* 2710. *(June* 1947, *published* 1953.)

Low-speed stability tests have been made on two wings of aspect ratio 4·5 and 3·0 (Models A and B). Both wings were of 45° sweepback, 4 : 1 taper ratio and 14 per cent. thickness ratio.—(10.2.2).

Experiments on the two-dimensional flow over a N.A.C.A. 0018 *profile at high angles of attack. H. Wijker. N.L.L. Report A.*1263.

Pressure distributions over the surface of a model with N.A.C.A. 0018 profile in two-dimensional flow were measured at a Reynolds number of about $2{\cdot}7 \times 10^6$. Transition points were found by the liquid film method and separation phenomenae were studied mainly with the aid of tufts. The lift coefficients at high angles of attack were calculated for a model with aspect ratio 6. The influence of the tunnel walls on the pressure distribution over the suction side was determined theoretically.—(1.10.2.1).

A method for determining cloud-droplet impingement on swept wings. R. G. Dorsch and R. J. Brun. N.A.C.A. Technical Note 2931. *(April* 1953.)

The general effect of wing sweep on cloud-droplet trajectories about swept wings of high aspect ratio moving at subsonic speeds is discussed. A method of computing droplet trajectories about yawed cylinders and swept wings is presented, and illustrative droplet trajectories are computed. A method of extending two-dimensional calculations of droplet impingement on nonswept wings to swept wings is presented.—(1.10.1.2).

AEROELASTICITY

The determination of the natural frequencies of a full-scale airframe-engine system by the admittance method. J. R. Forshaw and F. T. Mountford. R. & M. 2667. *(July* 1948, *published* 1953.)

The development of the method of the measurement of admittances and the solution of the frequency equation for a complex fullscale airframe-engine system is given, dividing the dynamical system at the attachment of the engine to the airframe, and using a force system of equal and opposite bending moments and shearing forces. The values of the resonance frequencies obtained from the graphical solution of the frequency equation and from the resonance test are compared and found to be in good agreement. The method is applicable to the matching of an engine to an airframe by adjusting the flexibility of the mounting units.—(2 × 33.1.2).

Lift developed on unrestrained rectangular wings entering gusts at subsonic and supersonic speeds. H. Lomax. N.A.C.A. Technical Note 2925. *(April* 1953.)

Lift forces induced by a vertical gust are estimated on the basis of theoretical calculations. The effects of pitching and

wing bending are neglected and only wings of rectangular plan form are considered. However, the effects of Mach number (from 0 to 2) and aspect ratio (2 to ∞) are included, and solutions are given by means of which the response to gusts having arbitrary streamwise gradients can be calculated. Results are presented for sharp-edged and triangular gusts and various wing-air density ratios.—(2 × 33.1.2).

FUELS AND LUBRICANTS

Effect of high bulk temperatures on boundary lubrication of steel surfaces by synthetic fluids. S. F. Murray, R. L. Johnson and E. E. Bisson. N.A.C.A. Technical Note 2940. (*May* 1953.)

An experimental study was made of the effect of high lubricant bulk temperatures on the boundary lubricating effectiveness of various types of synthetic fluids considered as lubricants for turbine engines.—(14.3).

HYDRODYNAMICS

Sur l'entretien des oscillations des eaux portuaires sous l'action de la haute mer. J. S. McNown. Publications Scientifiques et Techniques du Ministère de L'Air, France, No. 278. (1953.) (17.1.)

Estimation of hydrodynamic impact loads and pressure distributions on bodies approximating elliptical cylinders with special reference to water landings of helicopters. E. Schnitzer and M. E. Hathaway. N.A.C.A. Technical Note 1889. (*April* 1953.)

An approximate method for computing water loads and pressure distributions of lightly loaded elliptical cylinders during oblique water impacts is presented. The method, of special interest for the case of water landings of helicopters, makes use of theory developed and checked for landing impacts of V-bottom seaplanes.—(17.2).

Experimental investigation of the effect of rear-fuselage shape on ditching behavior. E. E. McBride and L. J. Fisher. N.A.C.A. Technical Note 2929 (*April* 1953.)

An experimental investigation was conducted to determine the effect of rear-fuselage shape on ditching behaviour. The basic fuselages were streamline bodies of revolution of fineness ratios 6 and 9. Variations in longitudinal curvature were obtained by sweeping up or sweeping down the rear half of the centre line. A change in the cross section was obtained by splitting the centre line in the plan view. The models were landed in calm water at speeds of 30, 40, 50 and 60 feet per second. The effects on ditching behaviour of changes in longitudinal curvature, cross section, fuselage fineness ratio, and landing speed are presented in terms of maximum height of the centre of gravity, maximum attitude, length of run, and skipping tendency.—(17.2).

Water-landing investigation of a flat-bottom V-step model and comparison with a theory incorporating planing data. R. W. Miller. N.A.C.A. Technical Note 2932. (*May* 1953.)

This paper presents the results of a fixed-trim smooth-water impacts of a flat-bottom V-step model having a high beam loading.—(17.2).

INSTRUMENTS AND EQUIPMENT

Static force-deflection characteristics of six aircraft tires under combined loading. W. B. Horne. N.A.C.A. Technical Note 2926.

Static force-deflection tests were made on six aircraft tyres. These tests included the vertical loading of the six tyre specimens, combined vertical loading and side loading and combined vertical loading and torsional loading of five tyre specimens, and combined vertical loading and fore-and-aft (longitudinal) loading of one tyre specimen for different initial inflation pressures. Tyre deflection, vertical-load centre-of-pressure shifts, and tyre pressure measurements are presented for the different load combinations.—(18.3).

MATERIALS

Effect of mean stress on the fatigue strength of D.T.D. 364 *round bars with and without transverse holes. G. M. Norris. A.R.C. Current Paper No.* 120. (*May* 1952, *published* 1953.)

Endurance curves for zero mean stress and for tensile mean stresses of 5 tons/in.^{2} and 10 tons/in.^{2} were determined for round specimens machined from extruded D.T.D. 364 bar. Endurance curves were determined also for similar specimens with a transverse hole. Variations in surface roughness caused some scatter in results and an attempt is made to correlate degree of surface finish with fatigue strength.—(21.2.2).

Some problems of the theory of creep. Y. N. Rabotnov. N.A.C.A. Technical Memorandum 1353. (*April* 1953.)

A theory of creep is proposed which represents an extension of the theory of elastic heredity of Volterra to plastic deformation. The theory is applied to the problems of relaxation, reverse creep, creep-bending of bars, and creep of a pipe under internal pressure. A special class of three-dimensional problems, in which the relative magnitudes of the stresses at a point remain constant with time, and likewise the relative magnitudes of the strains, is also considered.—(21.2 × 33.2.2).

Axial-load fatigue properties of 24*S-T and* 75*S-T aluminum alloy as determined in several laboratories. H. J. Grover, et al. N.A.C.A. Technical Note* 2928. (*May* 1953.)

In the initial phase of an N.A.C.A. programme on fatigue research, axial-load tests on 24S-T3 and 75S-T6 aluminium-alloy sheet have been made at the Battelle Memorial Institute and at the Langley Aeronautical Laboratory of the N.A.C.A. The test specimens were polished and unnotched. The manufacturer of the material, the Aluminum Company of America, has made axial-load tests on 24S-T4 and 75S-T6 rod material. The test techniques used at the three laboratories are described in detail; the test results are compared with each other and with results obtained on unpolished sheet by the National Bureau of Standards.—(21.2.2).

Relation between roughness of interface and adherence of porcelain enamel to steel. J. C. Richmond, et al. N.A.C.A. Technical Note 2934. (*April* 1953.)

The relationship between adherence and roughness of interface between enamel and iron was studied. Porcelain-enamel ground coats were prepared and applied under conditions that gave various degrees of adherence. The variations were produced by (*a*) varying the amount of cobalt-oxide addition in the frit; (*b*) varying the type of metallic-oxide addition in the frit, keeping the amount constant at 0·8 weight per cent.; (*c*) varying the surface treatment of the metal before application of the enamel, by pickling, sandblasting, and polishing; and (*d*) varying the time of firing of the enamel containing 0·8 per cent of cobalt oxide. A positive correlation was found between adherence and roughness of the interface.—(21.4 × 21.3.1).

MECHANICAL ENGINEERING

The calculation of whirling speeds of a system of rotors keyed to co-axial shafts. T. S. Wilson. R. & M. 2709. (*May* 1948, *published* 1953.)

This paper brings the calculation of whirling speeds of an important class of systems within the scope of an iterative technique and demonstrates by theory and example that problems involving large numbers of degrees of freedom may thereby be efficiently dealt with. An additional refinement of the procedure allows two or more modes to be extracted more or less simultaneously from an iteration which is converging slowly.—(23.1).

POWER PLANTS

Combustion instability in an acid-heptane rocket with a pressurized-gas propellant pumping system. A. O. Tischler and D. R. Bellman. N.A.C.A. Technical Note 2936. (*May* 1953.)

The low-frequency instability problem of a rocket using liquid propellants and a pressurized-gas propellant pumping system was experimentally investigated with a 300-pound thrust acid-heptane rocket. The results were compared to results predicted by an analysis based on the premise that the instability was due to an out-of-phase coupling between propellant flow and combustion-chamber pressure.—(27.3).

RESEARCH

See also AERODYNAMICS: COMPRESSIBLE FLOW

The Toepler schlieren apparatus. D. W. Holder and R. J. North. R. & M. 2780. (*April* 1950, *published* 1953.)

For wind-tunnel observations it is usually necessary that a Toepler schlieren apparatus shall have roughly uniform sensitivity to density gradients within a certain range determined by the nature of the flow. It is also desirable that the illumination in the image of the flow shall be as high as possible if visual observations are to be made under the best conditions and if photographs are to be taken with very short exposures. Methods for satisfying these two requirements are discussed and experimental results are included to illustrate their importance.—(31.1).

The Royal Aircraft Establishment 4 ft. × 3 ft. experimental low turbulence wind tunnel. Part I. General flow characteristics. H. B. Squire and K. G. Winter. R. & M. 2690. (*February* 1948, *published* 1953.)

The 4 ft. × 3 ft. wind tunnel was erected as a model of larger tunnels to investigate unconventional design features directed towards obtaining a high standard of flow. Diffusers of 5° cone angle are used, except for the rapid expansion through three wire gauze screens up to the maximum section. The contraction ratio is 31·2 : 1 and nine screens are fitted in the maximum section. A speed control is used operating independently of the fan by means of a by-pass duct.—(31.2.1).

STRUCTURES

See also AEROELASTICITY

THEORY AND ANALYSIS

Strain energy analysis of swept boxes with ribs normal to the spars. D. Howe. Cranfield Report No. 63. (*May* 1953.)

The root constraint problem associated with uniform rectangular swept boxes, having ribs normal to the spars is considered. A strain energy method using self-equilibrating internal end load systems is used. Solutions are presented for the cases of a single cell box having either all ribs rigid, or the root rib flexible. In addition, a consideration is made of second order effects combined with a flexible root rib. The case of a box having two equal cells, with all ribs rigid and a built in root is investigated, and the method of dealing with special root connections in this case is indicated. The effect of the flexibility of the root rib in the two cell box is also considered.—(33.2.3).

The diffusion of load into a panel bounded by constant stress booms and a transverse beam. E. H. Mansfield. R. & M. 2729. (*August* 1948, *published* 1953.)

A theoretical investigation is made into the diffusion of symmetrical, concentrated loads into a long stiffened panel having constant stress edge members and a transverse loading beam. Both pin-jointed and clamped end conditions for the beam are considered. Curves are given for determining the peak shear stress near the boom, the variation of this shear stress along the length of the panel, the proportion of load transferred by the beam, and the bending moment at the ends of the beam.—(33.2.3 × 33.2.4).

The buckling of triangular plates under combined compression and shear. J. Guest. A.R.L., Australia, Structures and Materials Note 203. (*March* 1953.)

The buckling condition is derived for simply supported right-angled triangles subjected to uniform normal tractions along the hypotenuse and a balancing system of uniform normal and shear tractions along the sides. Galerkin's method is employed. Numerical results are obtained for plates of side ratio a/b 0·8. Two cases are considered; that of uniform tension and that of uniform compression along the hypotenuse.—(33.2.4).

Deflection of delta wings having a carry-through-bay chord smaller than the wing root chord. R. W. Peters and M. Stein. N.A.C.A. Technical Note 2927. (*May* 1953).

Experimentally determined influence coefficients are presented for the deflection of two solid delta wings—one wing of constant thickness and the other of constant thickness ratio—having a carry-through-bay chord smaller than the wing root chord. A theoretical method of analysis is demonstrated for the constant thickness wing under tip load, and the theoretical results are compared with the experimental results.—(33.2.3).

Interim report on a fatigue investigation of a full-scale transport aircraft wing structure. M. J. McGuigan, Jr. N.A.C.A. Technical Note 2920. (*April* 1953.)

Results are presented of constant-level fatigue tests conducted on several full-scale C-46 "Commando" aeroplane wings at a level of $1 \pm 0{\cdot}625g$ or about 22 ± 14 per cent. of the design ultimate load factor. The average lifetime for the 34 fatigue failures that occurred was about 200,000 cycles. Effective stress concentration factors were calculated for all failures and indicated a value of about 4·0 for an inspection cutout and 2·3 for a riveted tension joint.—(33.2.3 × 33.3.2).

THERMODYNAMICS

Radiant-interchange configuration factors. D. C. Hamilton and W. R. Morgan. N.A.C.A. Technical Note 2836. (*December* 1952).

A study is presented of the geometric configuration factors required for computing radiant heat transfer between opaque surfaces separated by a non-absorbing medium and various methods of determining the configuration factors are discussed. Configuration-factor solutions available in the literature have been checked and the more complicated equations are presented as families of curves.—(34.3.1).

Calorimetric determination of constant-pressure specific heats of carbon dioxide at elevated pressures and temperatures. V. E. Schrock. N.A.C.A. Technical Note 2838. (*December* 1952).

The constant-pressure specific heat of carbon dioxide has been measured over the range of temperatures and pressures from ambient conditions to 1,000 lb./in.^{2} gauge and 1,000°F. using a steady-flow calorimeter operated on an open cycle. Only very limited calorimetric data are available in the literature, but substantial agreement exists with those considered reliable.—(34.2).

Study of pressure effects on vaporization rate of drops in gas streams. R. D. Ingebo. N.A.C.A. Technical Note 2850. (*January* 1953).

Vaporisation-rate and surface-temperature data were obtained for four pure liquids evaporating from the surface of a porous sphere in air streams having a static pressure range of 450 to 1,500 millimetres of mercury. Data were also obtained for methanol evaporating in streams of helium, argon, and carbon dioxide.—(34.1).

Laminar natural-convection flow and heat transfer of fluids with and without heat sources in channels with constant wall temperatures. S. Ostrach. N.A.C.A. Technical Note 2863. (*December* 1952).

An analysis of the natural-convection phenomenon shows that the flow and heat transfer, in general, not only are functions of the Prandtl and Grashof numbers but also depend on a new dimensionless parameter. If this parameter is not negligibly small, the compression work and frictional heating may appreciably affect this mode of heat transfer.—(34.3).

Heat and momentum transfer between a spherical particle and air streams. Y. S. Tang, J. M. Duncan and H. E. Schweyer. N.A.C.A. Technical Note 2867. (*March* 1953).

Heat-transfer coefficient for a spherical particle heated by an induction coil in a moving air stream were experimentally determined for the Reynolds number range from 50 to 1,000 using spheres of $\frac{1}{4}$ to $\frac{5}{8}$ in. diameter and air velocities from 1 to 13 feet per second. A correlation of the heat-transfer factor or Stanton number with the Reynolds number was obtained and expressed by an empirical equation.—(34.3.2).

Analysis of heat addition in a convergent-divergent nozzle. D. P. Hearth and E. Perchonok. N.A.C.A. Technical Note 2938. (*April* 1953.)

The effect of heat addition to a divergent stream with initially sonic flow is analysed and the variation of exit Mach number, static pressure, and total pressure is presented.—(34.4).

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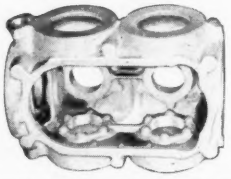

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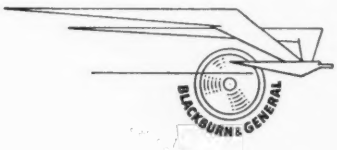

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